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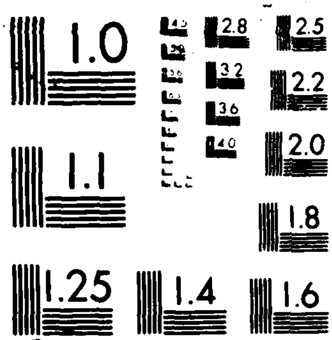
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DEPARTMENT OF ELECTRICAL AND COMPUTER ENGINEERING
COLLEGE OF ENGINEERING AND TECHNOLOGY
OLD DOMINION UNIVERSITY
NORFOLK, VIRGINIA 23508

MAGNETIC CONTROL OF LOW PRESSURE DISCHARGES

By

Karl H. Schoenbach, Principal Investigator

Annual Report
For the period ending August 15, 1987

Prepared for the
Department of the Navy
Office of the Chief of Naval Research
800 North Quincy Street, Code 1112
Arlington, Virginia 22217-5000

Under
Department of the Navy
Contract No. N00014-85-K-0602
B. R. Junker, Scientific Program Officer
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In abnormal glow discharges, operated in electronegative gas mixtures, the discharge resistance can be increased by the application of a transverse magnetic field. This effect is caused by a shift of the electron energy distribution towards lower energies. In the positive column of the discharge this leads to a reduction of electron drift velocity and ionization rate, and for certain attachers, an increase of the attachment rate and consequently to an increase of the resistivity.

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A coaxial discharge system was used to study the steady-state and transient behaviour of abnormal glow discharges in a He:SF_6 gas mixture in transverse magnetic fields. The steady-state current characteristics were measured for current densities up to A/ cm^2 and magnetic field intensities up to 1.2 Tesla. At current densities of 1 A/cm^2 and an interelectrode distance of 2 cm, the discharge voltage was found to increase with a rate of 2 kV/Tesla, corresponding to an increase of electric field intensity of 1 kV/Tesla/cm.

The transient behaviour of the discharge was studied using oscillating magnetic fields with a maximum rise of 1 Tesla/microsecond. It was found that above a critical rise of 0.2 Tesla/microsecond the magnetic field caused a reduction in discharge resistance due to induced electric fields. For slower magnetic fields the discharge resistance increased in accordance with the steady-state characteristics.

In order to model the steady-state behaviour of glow discharges in transverse magnetic fields, Monte-Carlo codes were developed for both the positive column and the cathode fall. A continuum model was used to calculate particle densities, current densities and electric field distribution along the discharge axis. The computational results agreed well with the experimental values.

Experimental and theoretical results indicate, that a magnetically controlled discharge, where the control mechanism is based on the shift in the positive column electron energy distribution, can be utilized as an opening switch with opening times in the range of hundred microseconds. Another way to utilize the control effect is to shorten the afterglow of low pressure closing switches in the microsecond range.

Another promising magnetic control mechanism seems to be possible in hollow cathode discharges. Measurements on single hole hollow cathode discharges showed three distinct pressure regions with currents differing by four orders of magnitude. In order to switch between the different discharge modes, it seems to be necessary to modify the motion of ions which are responsible for the generation of electrons at the cathode. Necessary magnetic inductions are in the order of one Tesla. The advantage of hollow cathode discharges is the potentially high current density of several hundred A/cm^2 in a multihole arrangement and its high stability.

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INTRODUCTION

The effect of transverse magnetic fields on glow discharges has been studied since the late nineteenth century [1]. Most of the experimental work has been done in systems which operate on the low p*d side (left hand) of the sustaining voltage minimum, where p is the pressure and d is the electrode spacing. On the left-hand-side of the p*d minimum, the application of a transverse magnetic field decreases the discharge potential. This effect has been sucessfully used in closing and opening switches [2] and to reduce the forward potential of cold cathode tubes [3].

Very little work has been done on the high p*d side of the voltage minimum. In this range the application of a transverse magnetic field increases the dielectric strength of a gas [4] and it increases the discharge potential, as stated as early as 1933 by Thomson in his book "Conduction of Electricity through Gases" [5]. More recent measurments of the potential of He-discharges in transverse magnetic fields have been performed by Turnquist [6]. The effect on the discharge potential can be explained by tne shift of the electron energy distribution towards lower energy values in crossed electric and magnetic fields [7]. This shift causes a reduction of the drift velocity and a decrease of the ionization rate. In the positive column of the glow discharge, which can be considered a homogeneous plasma, the resistivity is increased by this mechanism and so is the discharge potential at constant or even decreasing current. To enhance this effect an attacher with a large attachment cross section at low energies may be used. The shift of the electron energy distribution in crossed fields stimulates increased attachment, a process which reduces the conductivity in the positive column further.

The effect of magnetic fields on the cathode fall of a glow discharge, operated at p*d values above that for minimum sustaining voltage is less understood than its effect on the positive column. With increasing current densities (abnormal glow), however, the cathode fall voltage determines more and more the discharge potential. Considerations of the change of the electron energy distribution in crossed fields as used to discuss the variation in the sustaining electric field in the positive column are not sufficient to predict the behaviour of the cathode fall in transverse magnetic fields. Models which take nonequilibrium effects into account have to be used in order to describe the influence of gas and electrode properties on the cathode fall [8, 9].

The modeling of the cathode fall leads ultimately to discharge systems which are completely space charge dominated, such as hollow cathode discharges. Research on the effect of magnetic fields on hollow cathode discharges is in its infancy [10]. The study of such systems is not just important for control of discharge resistance but also to understand the charged particle behaviour in nonplanar boundary layers, e.g. in cavities on the surface of space vehicles.

EXPERIMENTAL SET-UP

A) COAXIAL SYSTEM

A coaxial configuration (Fig. 1) was chosen because it provides an easy way to generate a crossed field situation by using a solenoidally shaped coil. The $\vec{E}\times\vec{B}$ drift in this system leads just to a rotation of the plasma but not, at least in a first approximation, to charge separation and therefore to a build-up of space charge fields in the positive column.

The discharge circuit consists of a 50 Ω cable and a mid-plane triggered spark gap, which delivers a 200 ns pulse to a 70 Ω shielded resistor in series with the discharge chamber. In order to obtain longer pulses a 10 μs pulse forming network was also used.

Both the discharge voltage and current were recorded using transient digitizers and the magnetic field circuit current was recorded using a storage oscilloscope on every shot. The current waveforms were measured using commercial Rogowski coil current transformers. The discharge voltage was monitored by a capacitive voltage divider in series with a resistive voltage divider. This device has a fast risetime which is limited by the self inductance of the two carbon resistors in the resistive part of the divider. A cross-sectional view of the voltage divider is shown in Fig. 2. The step response of this device is an exponentially decaying signal which has a time constant equal to the product of the sum of the two resistors times the sum of the two capacitors. For short pulses (<60 ns) the voltage divider provides an accurate reproduction of the input signal. Longer signals must be processed digitally to compensate for the decay.

Figures 3a and 3b are plots of the voltage and current waveforms for four consecutive data points taken under the same conditions. The gas

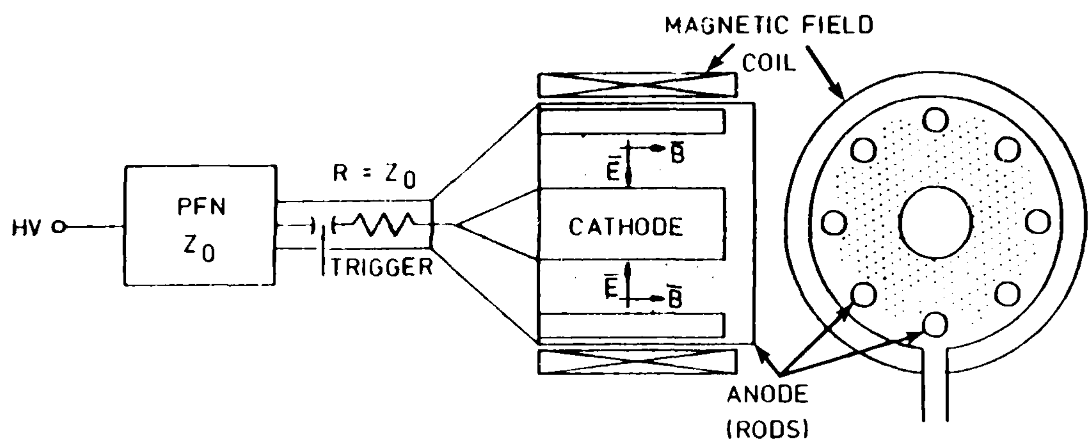

Fig. 1 Discharge circuit and discharge chamber cross-section.

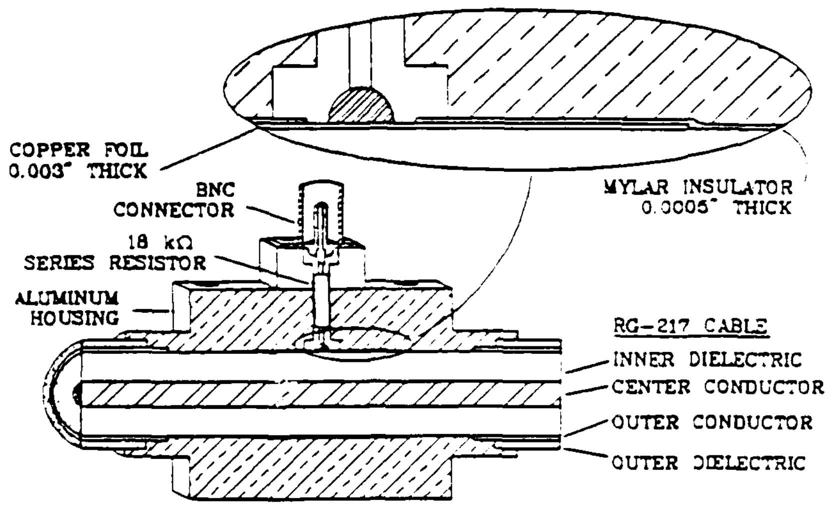

Fig. 2 Isometric drawing of the capacitive voltage divider.

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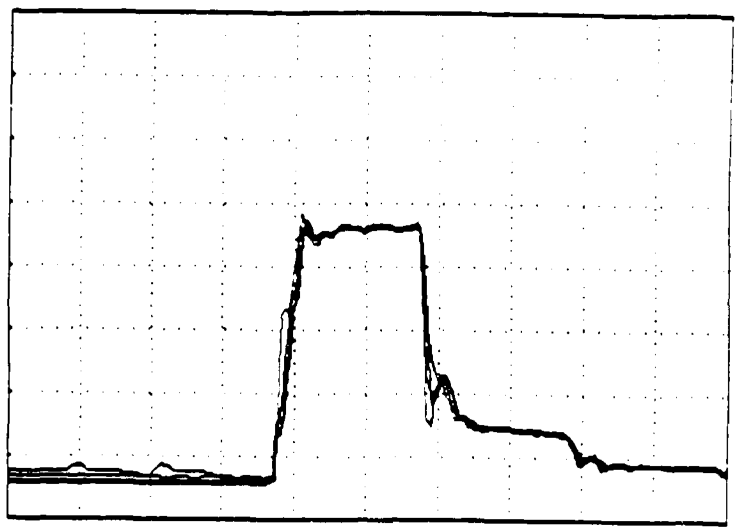

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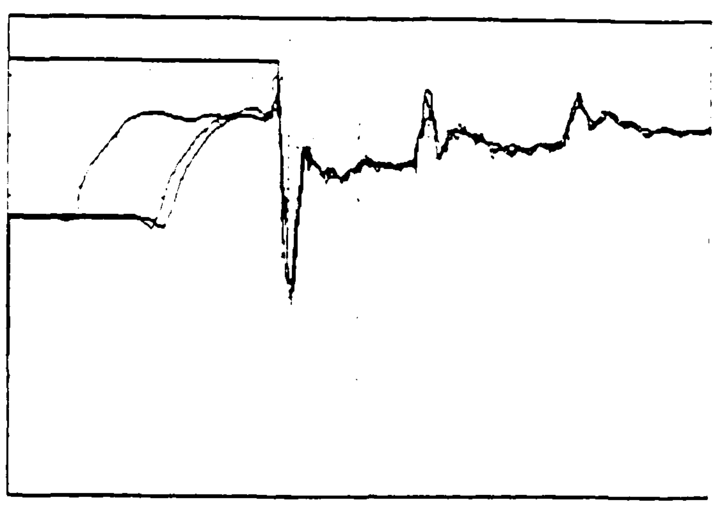


Fig. 3 Typical discharge (a) voltage and (b) current waveforms showing four consective shots superimposed.
20% SF_6 - 80% He, B = 0.05 Tesla, 100 ns/div,
(a) 618 V/div and (b) A/div.

mixture was 20% SF_6 • 80% He and the applied magnetic field was 0.05 Tesla. The jitter in the original waveforms was corrected by aligning three of the waveforms with the first using an interactive graphics program. The difference in the first 350 ns of the voltage waveforms is due the statistical delay of the discharge initiation.

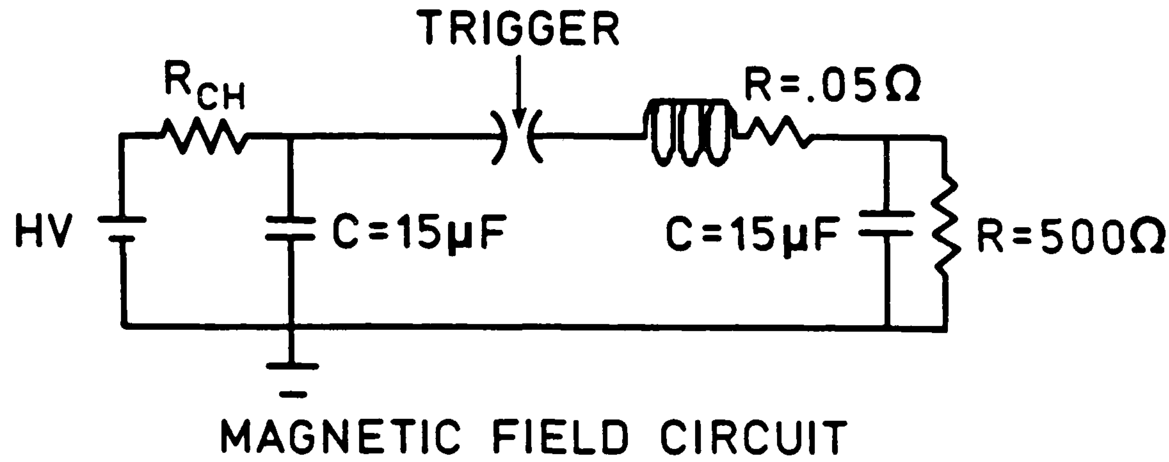
To study the steady-state behaviour of the radial glow discharge, with current densities up to A/cm^2, in transverse magnetic fields a "quasi-dc" axial magnetic field was applied. The experimental set-up has been described in reference [7]. The magnetic field circuit is a series RLC circuit capable of delivering peak currents of 2.2 kA, which produced magnetic fields in excess of 1.2 Tesla.

A second magnetic field circuit has been built recently. This circuit consists of a single turn coil and a three-turn coil powered by a capacitor. This system allows to generate magnetic fields of up to 1.5 Tesla with risetimes of the order of 1 microsecond. The magnetic field circuit and the two types of coil currents used in our experimental studies are shown in Figs. 4a and 4b.

B) LINEAR SYSTEM

A second system with plane-parallel electrodes was designed and built in order to study the cathode fall in abnormal glow discharges and the effect of longitudinal magnetic fields on hollow cathode discharges. In such a configuration longitudinal magnetic fields can easily be generated by using a solenoid with its axis along the discharge axis or in case of a hollow cathode discharge along the hole in the cathode.

The discharge system consists of a coaxial discharge chamber with plane parallel electrodes (Fig. 5). For hollow cathode investigations a hole of



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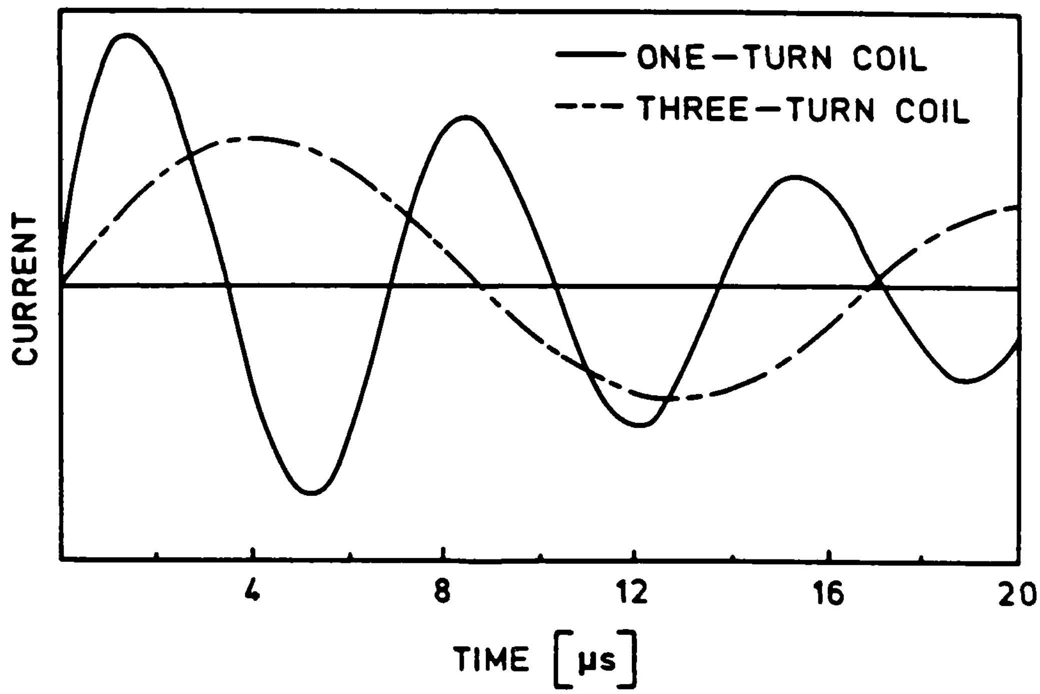


(4b)

Fig. 4 (a) Magnetic field circuit and (b) Current waveforms obtained with one- and three-turn coils.

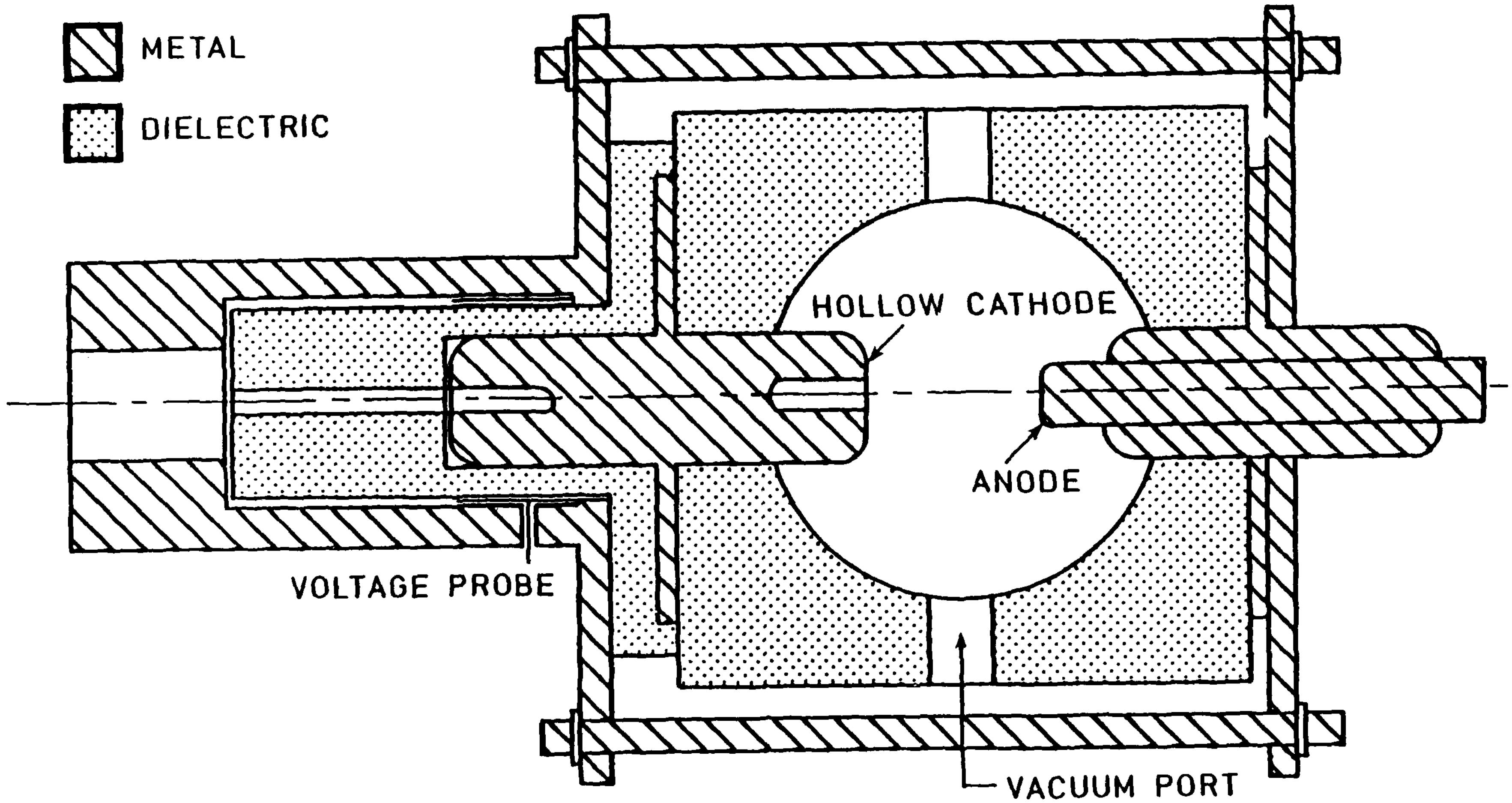


Fig. 5 Cross-section of the linear discharge-chamber.

0.5 cm diameter and 2 cm depth is drilled in one of the electrodes. The discharge is driven by a 50 Ohm, 10 microsecond pulse forming network (PFN) through a spark gap switch. A matching load resistance of 50 Ohm is placed in series with the discharge. The magnetic field circuit is a critically damped, series RLC circuit capable of delivering a peak current of 300 A which generates a magnetic field of 0.3 Tesla. The discharge current and the current in the magnetic field circuit was measured with Pearson coils and were recorded with 400 MHz Transient Digitizers.

EXPERIMENTAL RESULTS

A. THE EFFECT OF STATIC MAGNETIC FIELDS ON THE DISCHARGE IMPEDANCE

To determine the operating pressure of the gas in the discharge chamber, pressure versus discharge voltage data were taken. Figure 6 shows the measured values of pressure versus sustaining voltage for a current density of 1 A/cm^2 in SF_6, He and an 80% He - 20% SF_6 mixture. While these curves should not be confused with Paschen curves (which are pd versus sparking voltage), the curves for SF_6 and the SF_6:He mixture show the typical Paschen curve shape. There is a minimum voltage which increases as the pressure is either increased or decreased. The minimum voltage for SF_6 and the SF_6/He mixture are 1100 V and 1200 V, respectively. The He curve has its minimum at a pressure greater than 20 torr. In our studies we have concentrated on the He:SF_6 gas mixture, because discharges in this mixture are more stable than those in pure SF_6. The pressure was chosen to 8 Torr, just to the right of the minimum in the discharge potential curve (Fig.6).

Figure 7 is the measured quasi steady-state voltage current characteristics for the discharge in 20% SF_6 - 80% He with applied transverse

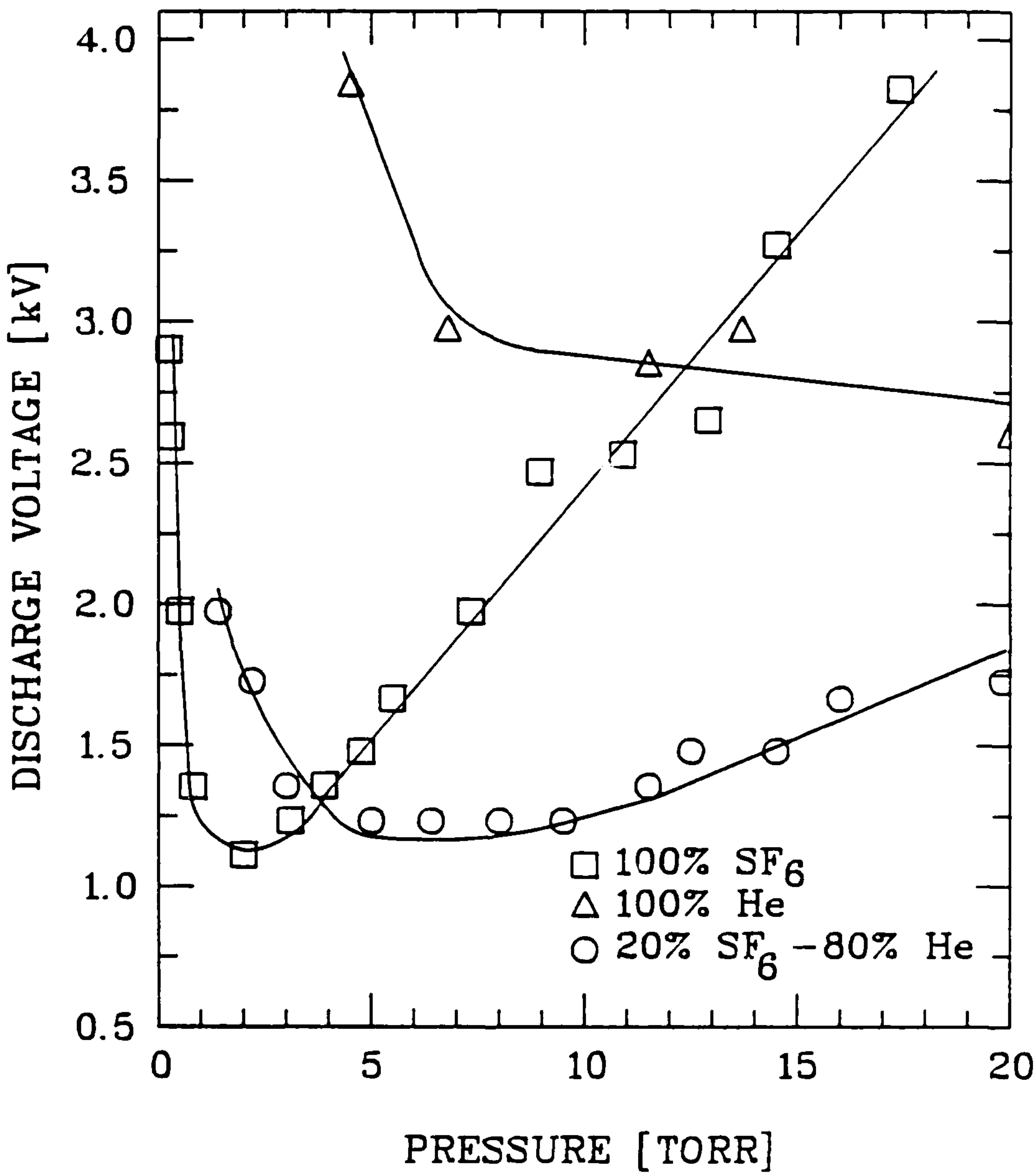


Fig. 6 Experimental values of discharge voltage as a function of gas pressure for various gases. Discharge current is 100 A.

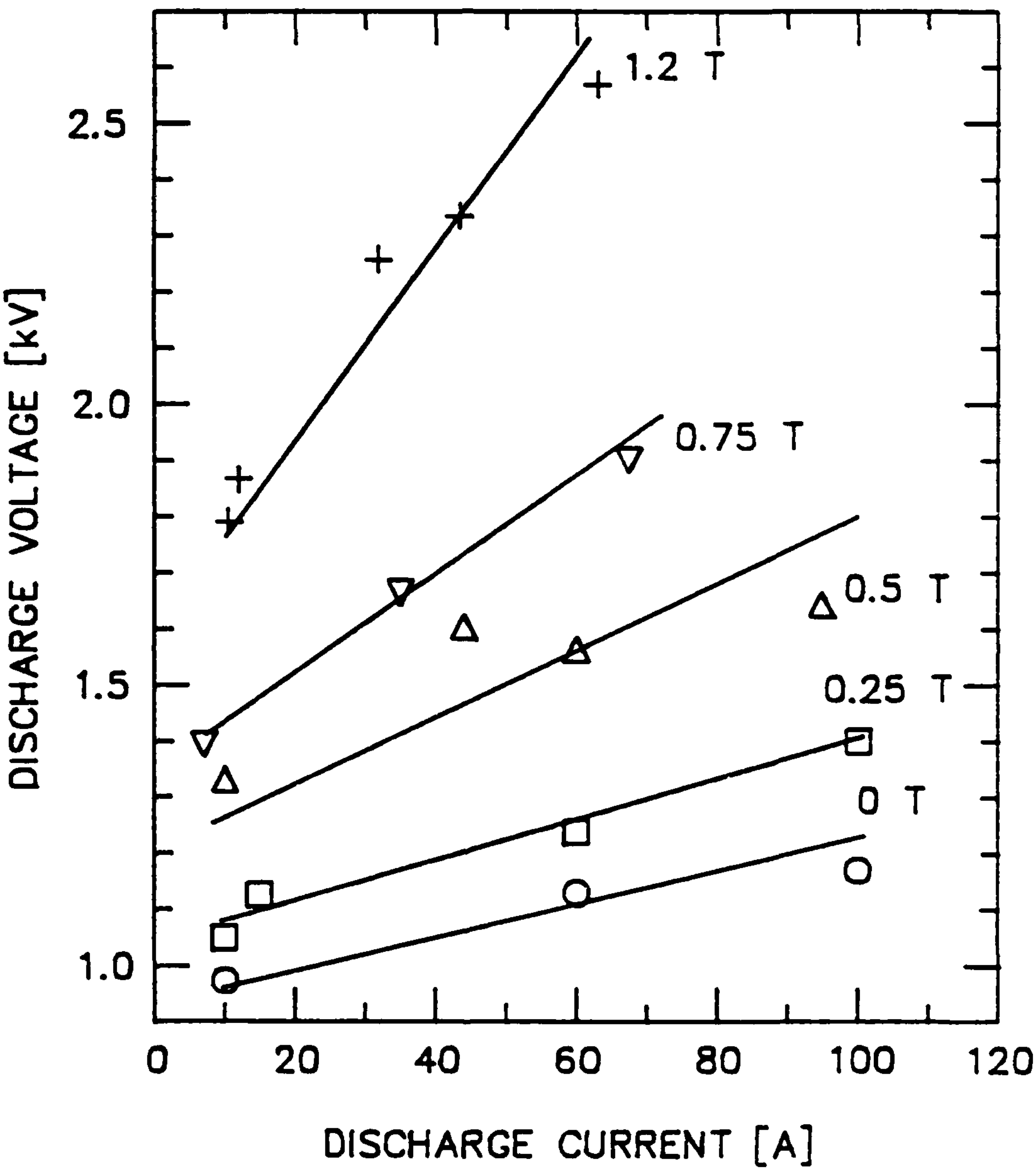


Fig. 7 Experimental values of discharge voltage as a function of discharge current in an 80% He - 20% SF_6 gas mixture at 8 torr for various values of transverse magnetic field intensity.

magnetic field. The measurements were made by recording both the discharge current and voltage waveforms for values of applied voltage at specific values of magnetic field intensity. Several data points were taken for each value of applied voltage. The statistical spread of the data is approximately 15%.

The relationship between the discharge voltage and the applied magnetic field strength at constant discharge current was determined from Figure 7. These data are given as Figure 8 for discharge currents of 20 A, 60 A and 100 A. With a cathode surface area of 100 cm^2, the corresponding current densities were 0.2 A/cm^2, 0.6 A/cm^2 and 1.0 A/cm^2, respectively. The plot shows an initial increase in discharge voltage with respect to magnetic field (dV/dB) of approximately 0.4 kV/Tesla for the three values of current. This increase to a steady value which is dependent on the discharge current. The final values of dV/dB for the three values of current are listed below.

I	dV/dB	B
20 A	1.6 kV/Tesla	$0.5 < B < 1.2$ Tesla
60 A	2.3 kV/Tesla	$0.6 < B < 1.2$ Tesla
100 A	2.6 kV/Tesla	$0.5 < B < 0.65$ Tesla

B. THE EFFECT OF TRANSIENT MAGNETIC FIELDS ON THE DISCHARGE IMPEDANCE

In order to study the effect of a transient magnetic field on the impedance of a gas discharge in $He:SF_6$, a capacitive discharge system was used, which allows the generation of magnetic fields up to 1.5 Tesla with risetimes in the microsecond range (see section: Experimental Set-up). The application of a transient axial magnetic field causes an azimutnal electric field in the discharge:

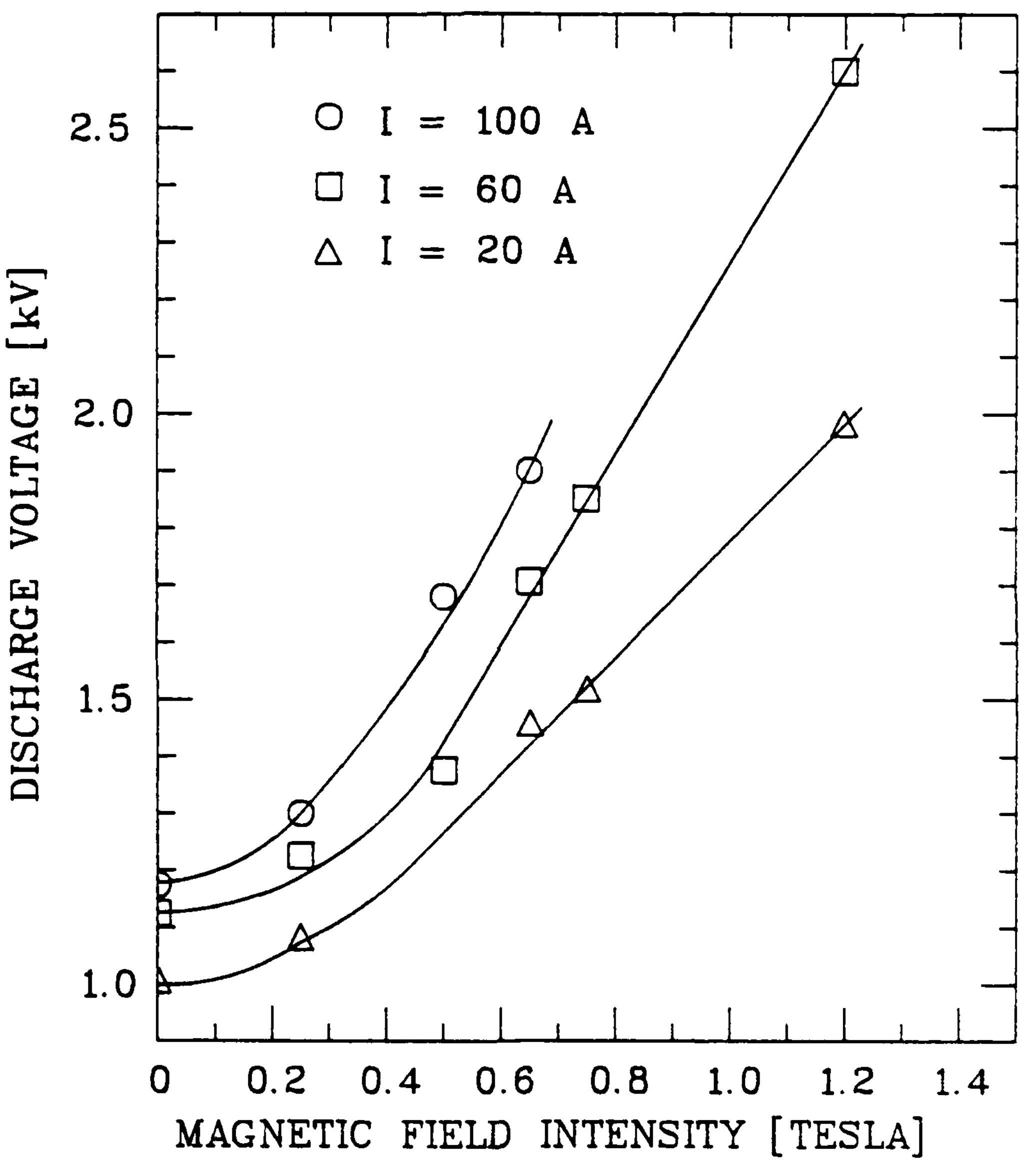


Fig. 8 Experimental values of discharge voltage as a function of applied transverse magnetic field intensity in an 80% He - 20% SF_6 gas mixture at 8 torr for various values of discharge current.

$$E_d = - (r/2)^* (dB/dt)$$

The induced electric field adds vectoriell to the radial electric field of the discharge. For fast rising magnetic fields the shift of the electron energies towards larger values due the induced electric field dominates over the oppositely directed magnetic field effect and the discharge conductance increases. This effect was observed when the temporal rate of change in the magnetic field intensity (dB/dt) reached values of 0.2 Tesla/microsecond, corresponding to an induced axial field strength of 170 V/cm at the outer electrode (r = 3.5 cm), which comes close to the order of magnitude of the applied radial electric field at this radial position.

With magnetic fields having a maximum rate of change of 0.1 Tesla/microsecond the expected opening effect was observed. Figures 8 and 9 show the temporal change in current, voltage and, derived from these quantities, the discharge resistance (Fig. 10). The resistance increases with increasing magnetic field, however, the discharge becomes unstable at a certain voltage and changes into the high conductance mode as in the case of high dB/dt. Figure 11 shows the current-voltage curve with the magnetic induction as parameter, in the steady-state characteristics diagram. The switching I-V curve follows the loadline of the circuit used in this experiment. The magnetic field intensity values corresponding to the I-V values on this curve are in agreement with the B-values of the steady-state curves. This indicates that the relaxation time of the electrons in a gas discnarge in transient magnetic fields is smaller than the characteristic time of change of the magnetic field.

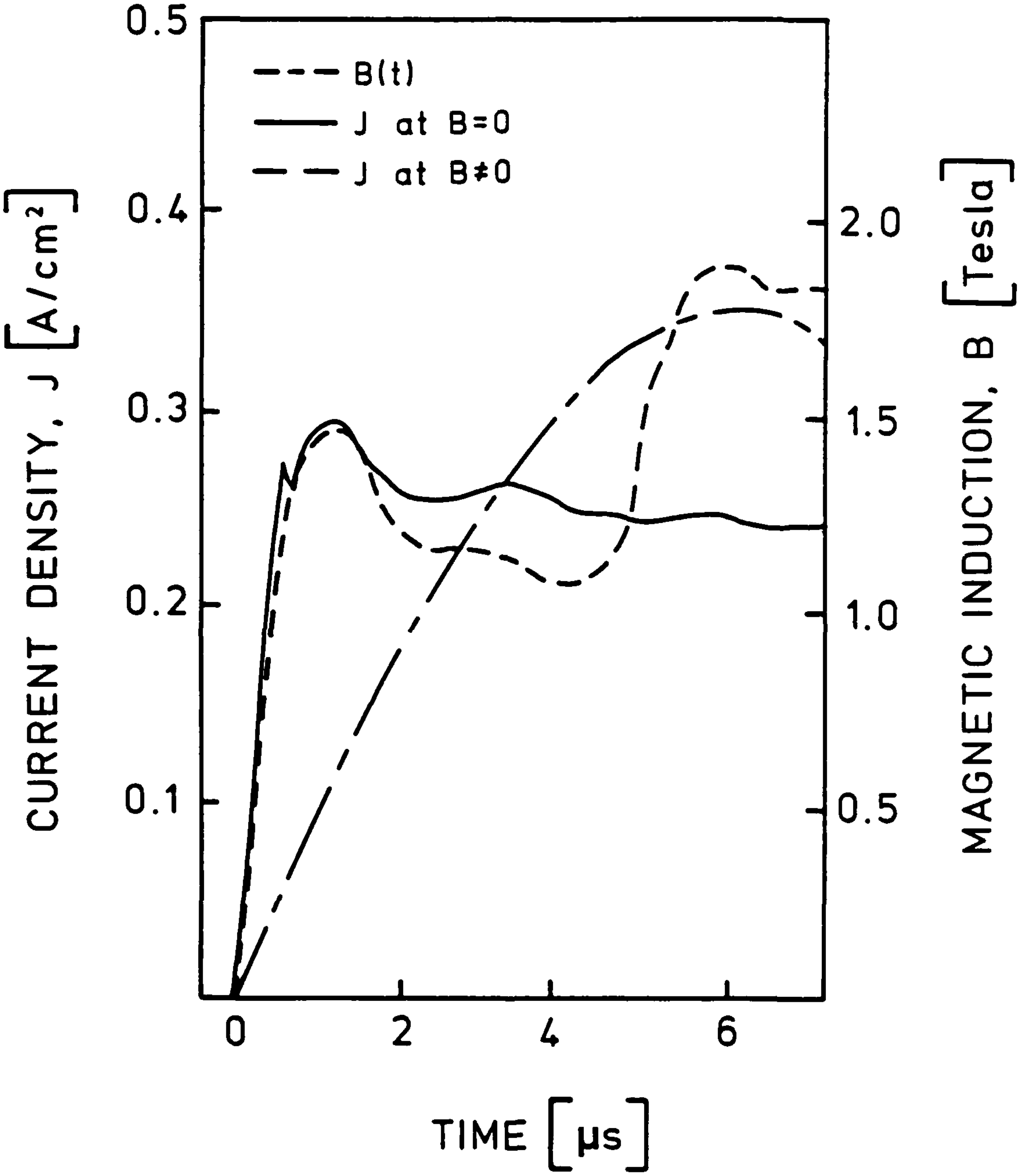


Fig. 9 Temporal development of the discharge current density with and without magnetic field B(t).

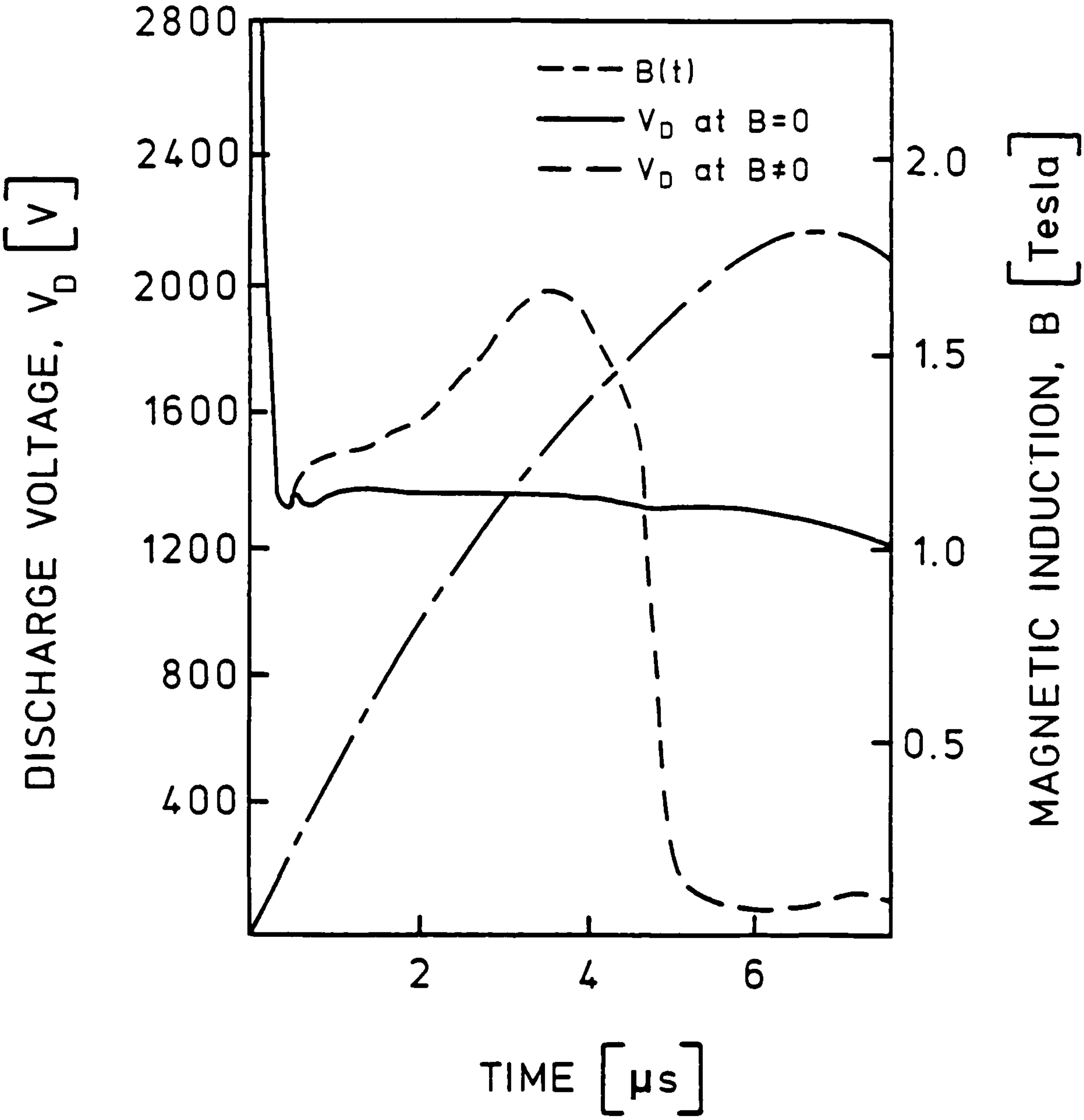


Fig. 10 Temporal development of the discharge voltage with and without magnetic field B (t).

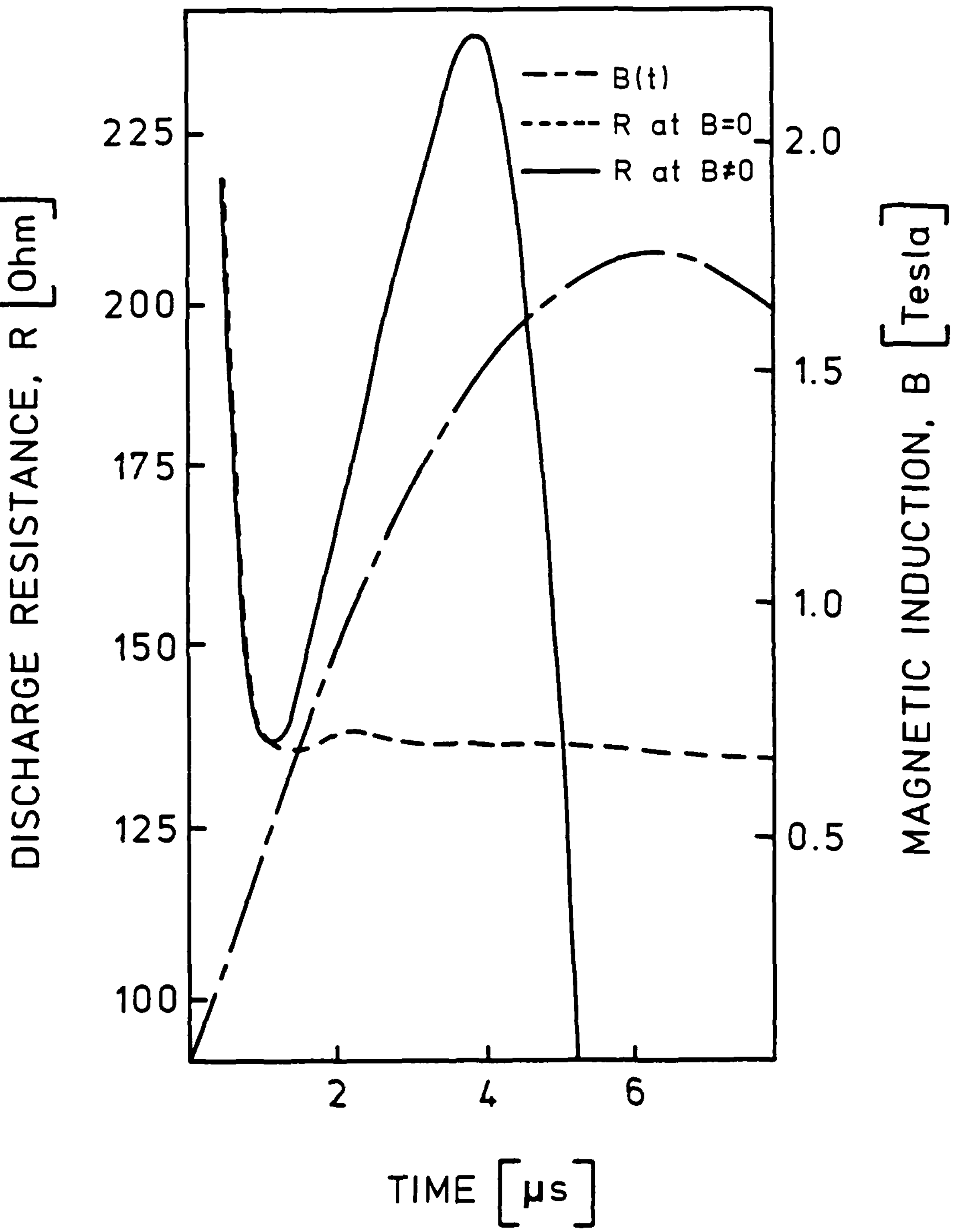


Fig. 11 Temporal development of the discharge resistance with and without magnetic field B(t).

C. THE EFFECT OF LONGITUDINAL MAGNETIC FIELDS ON A HOLLOW CATHODE DISCHARGE

A linear discharge system (Fig. 5) was used to study the pressure dependence of discharges between a plane anode and a hollow cathode and the influence of magnetic fields on the voltage-current characteristics of such discharges. The gas discharges utilizing a cathode with a cylindrical hole of .48 cm in diameter and 1.9 cm depth exhibits three distince modes of operation in He in the pressure range between 15 mTorr and several Torr (Fig. 12).

At pressures in the range of 15 to 70 mTorr the discharge carries a current of 120 Amperes at an impedance small compared to 50 Ohms. The diameter of the discharge channel is identical with the hole diameter (Fig. 13a). At pressures above 70 mTorr up to about 200 mTorr the discharge operates in a high impedance mode with currents four orders of magnitude less than in the previous mode of operation. In the high impedance mode a filamentary plasma of 0.1 cm diameter, immersed in a glow, was observed in the axis of the discharge system (Fig. 13b). This luminous phenomenon is probably caused by an electron beam emanating from the bottom of the hollow cathode [13]. In this mode of operation the discharge (electron-beam) current increased linearly with pressure. In the pressure range between 200 mTorr and 1 Torr the discharge is not well defined. It seems to set on the triple point (gas, electrode, dielectric). At pressures above 1 Torr, the discharge switched again into a high current, low impedance mode. A current of 60 Amperes was measured in this mode. It does not vary with pressure up to several Torr.

The high pressure, high current mode is in our opinion the common hollow cathode discharge mode, where the cathode fall distance corresponds to

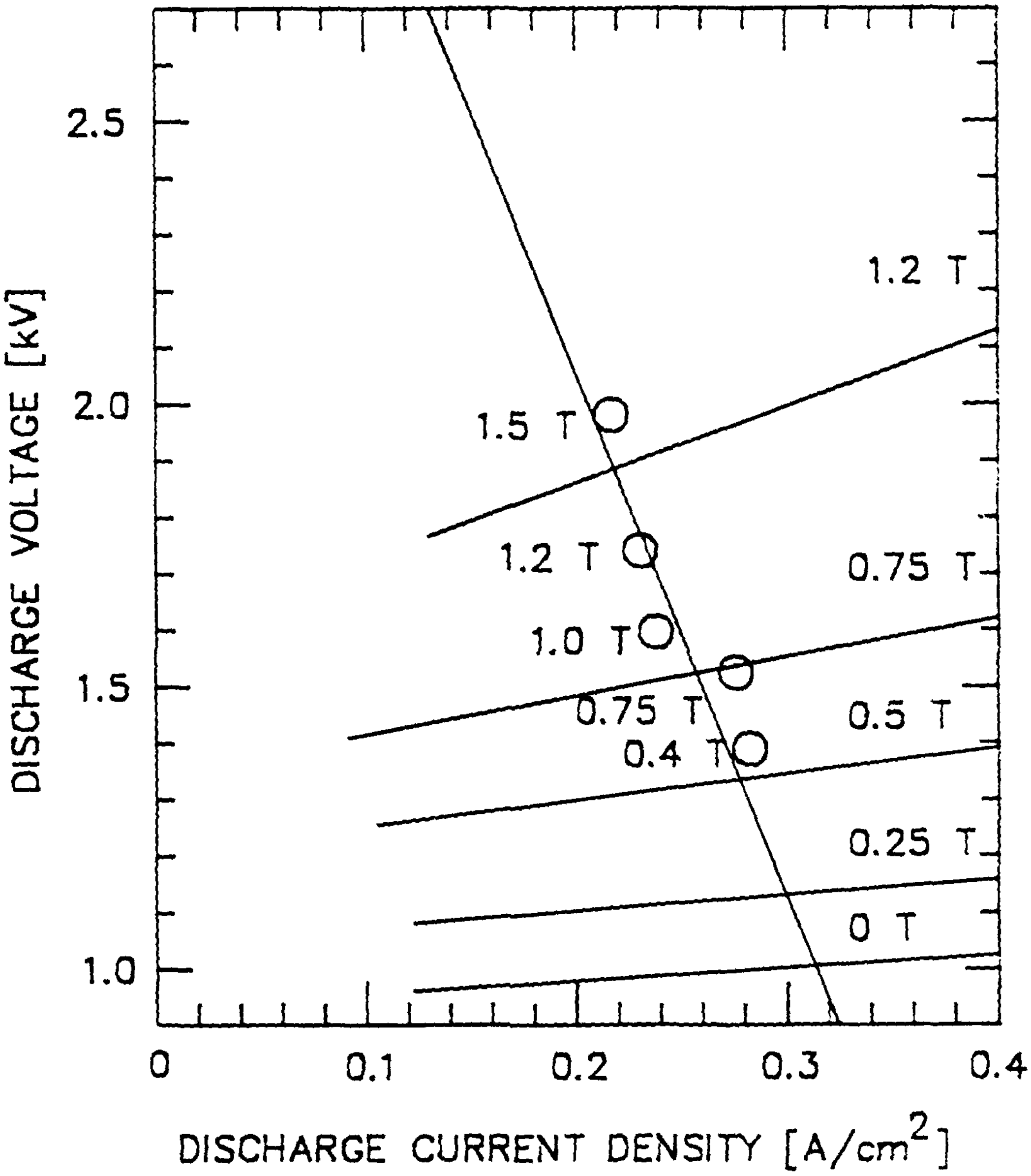


Fig. 12 Steady-state current voltage characteristics of magnetically controlled discharge with transient current-voltage curve that follows the load line of the discharge system.

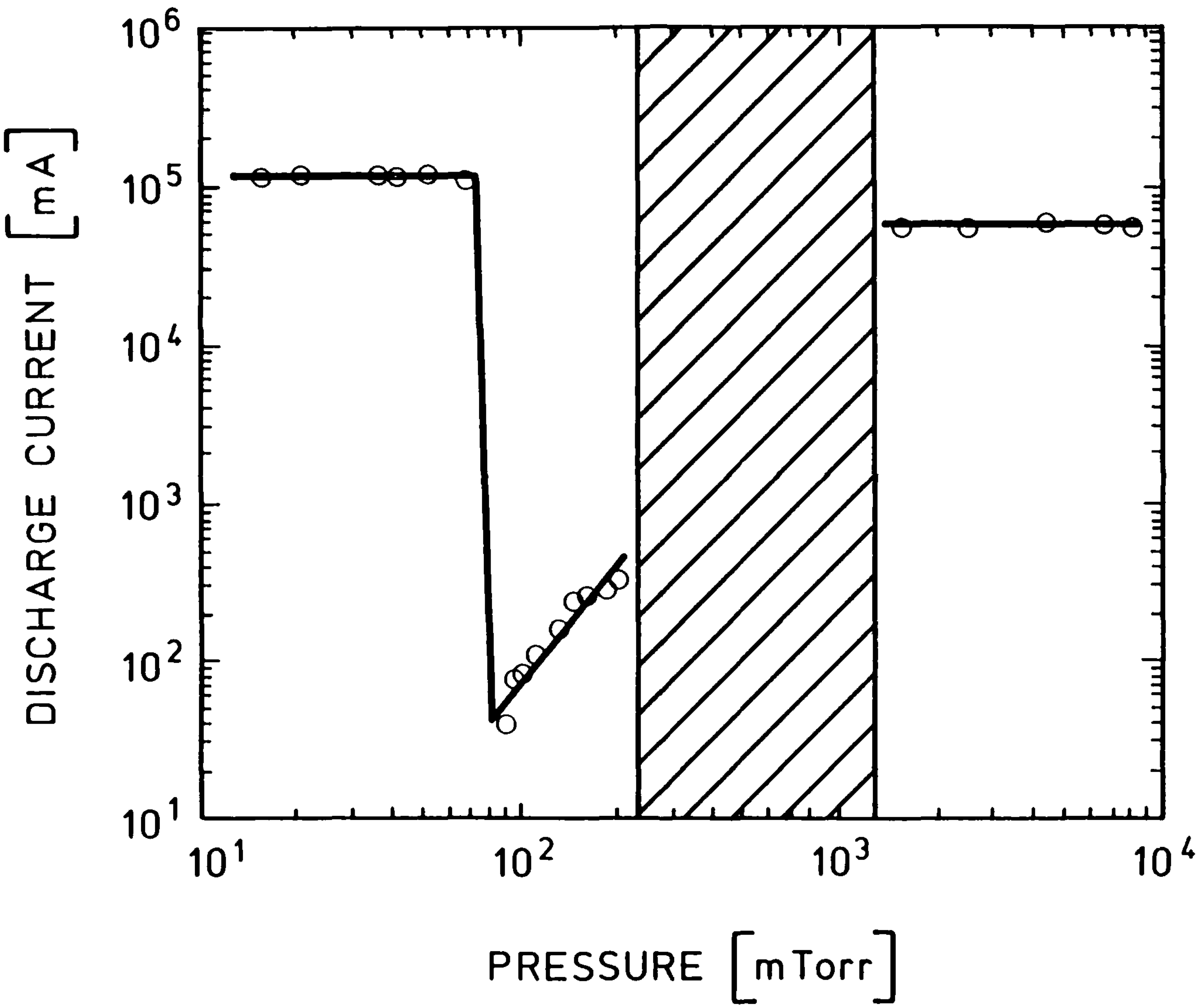


Fig. 13 Discharge current as a function of pressure. The hatched region defines the pressure range when the discharge sets on at the triple point. The current-pressure curve is not well defined in this region.

the radius of the hole in the cathode [11]. At lower pressures the formation of a space charge layer (cathode fall) is suppressed and the electrons, which are generated at the bottom of the hole are accelerated in the electric field between anode and cathode. This low current mode of operation is equivalent to the operation of an electron-beam diode with electron-generation through ion bombardment of the cathode. The high current discharge at very low pressures (< 70 m Torr) is probably a vacuum discharge, a discharge which is sustained in electrode material vapor.

Experiments have been performed to study the effect of axial magnetic fields on the discharge characteristics in the three observed modes of operation. With so far maximum obtainable magnetic fields of 0.3 Tesla in this configuration there was no change in the discharge characteristics of the "vacuum" and "hollow cathode" discharges. In the "electron-beam" mode (medium pressures), on the other hand, even small magnetic fields of 150 Gauss reduced the current by a factor of two. Because of the small current densities (several hundred milliamperes per square centimeter in a multihole structure), however, there does not seem to be an application of this effect in Pulsed Power opening switches.

If it becomes possible, however, to switch between the different modes of operation, changes in the impedance of almost four orders of magnitude can be expected. In order to influence the discharge in the pressure range about and below 1 Torr by means of magnetic fields, it is necessary to modify the motion of the ions which are responsible for the electron generation at the cathode. A criterion for an effective change of the ion path in the hollow cathode is given by the condition that the ion Gyroradius should be smaller than the hole radius. For He with an assumed average energy of 100 eV (several times the ionization energy) and a hole radius of 0.24 cm

the magnetic induction necessary to force the ions on a circle of the same radius is B = .85 Tesla. This value can be reduced if holes with a larger diameter are used which requires operation at lower pressures.

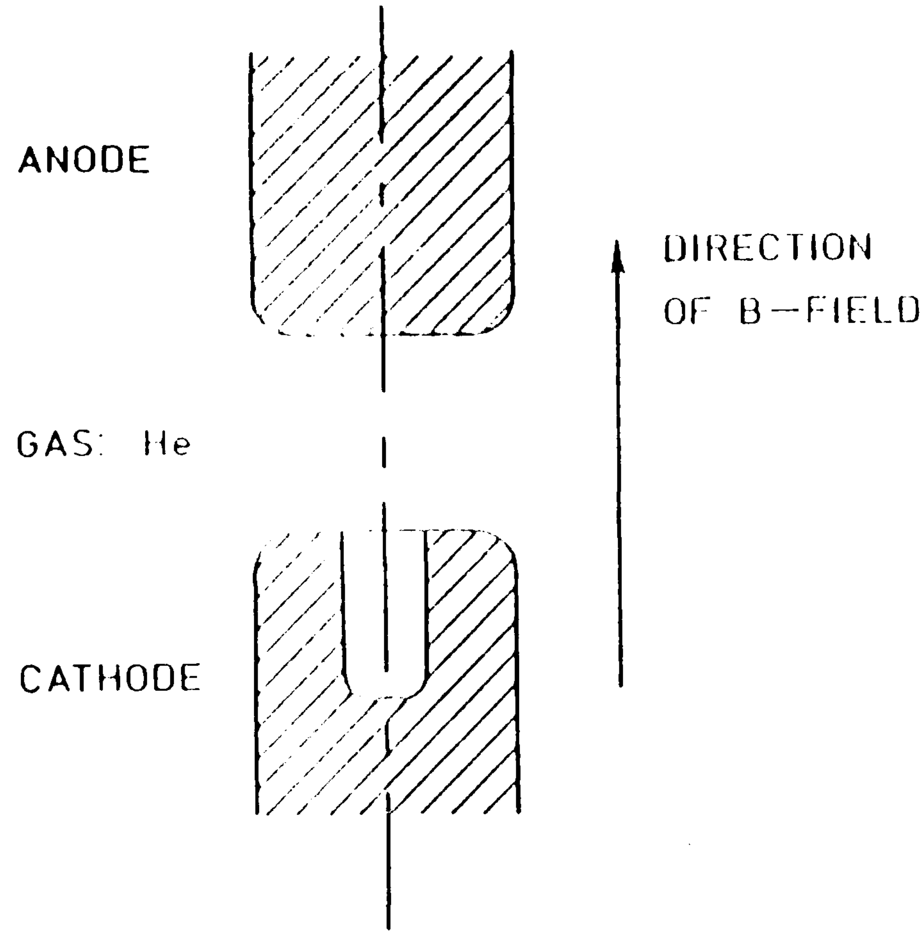
Assuming that discharges emanating from different holes in a cathode do not interact with each other, a possible pulsed power opening switch could consist of a plane anode and a multihole cathode. With such a configuration current densities of several 100 A/cm^2 seem to be obtainable. Furthermore, as measurements with 10 microsecond pulses indicate, these discharges are very stable.

COMPUTATIONAL RESULTS

Monte Carlo calculations were performed to simulate the positive column and the cathode fall of glow discharges in transverse magnetic fields. The gas mixture, which was chosen for our studies, was 20% SF_6 - 80% He at a pressure of 10 torr. SF_6 data compiled by Kline [12] and Phelps [13] were used. The cross sections for He, which serves as buffer gas, were taken from a paper by Hayashi [14].

A. POSITIVE COLUMN

A zero dimensional Monte-Carlo code was used to calculate the electron-energy distribution, ionization rate coefficient, attachment rate coefficient, collision frequency and drift velocity in the positive column [7, 15]. The computed attachment and ionization rate coefficients were used in a simplified continuity equation for electrons, where detachment, recombination and diffusion processes are neglected. This equation resulted in the calculation of the equilibrium reduced field strength, E/N, for the positive column of a discharge plasma as a function of the reduced magnetic field intensity, B/N. The results from such calculations are shown in Fig. 15 for



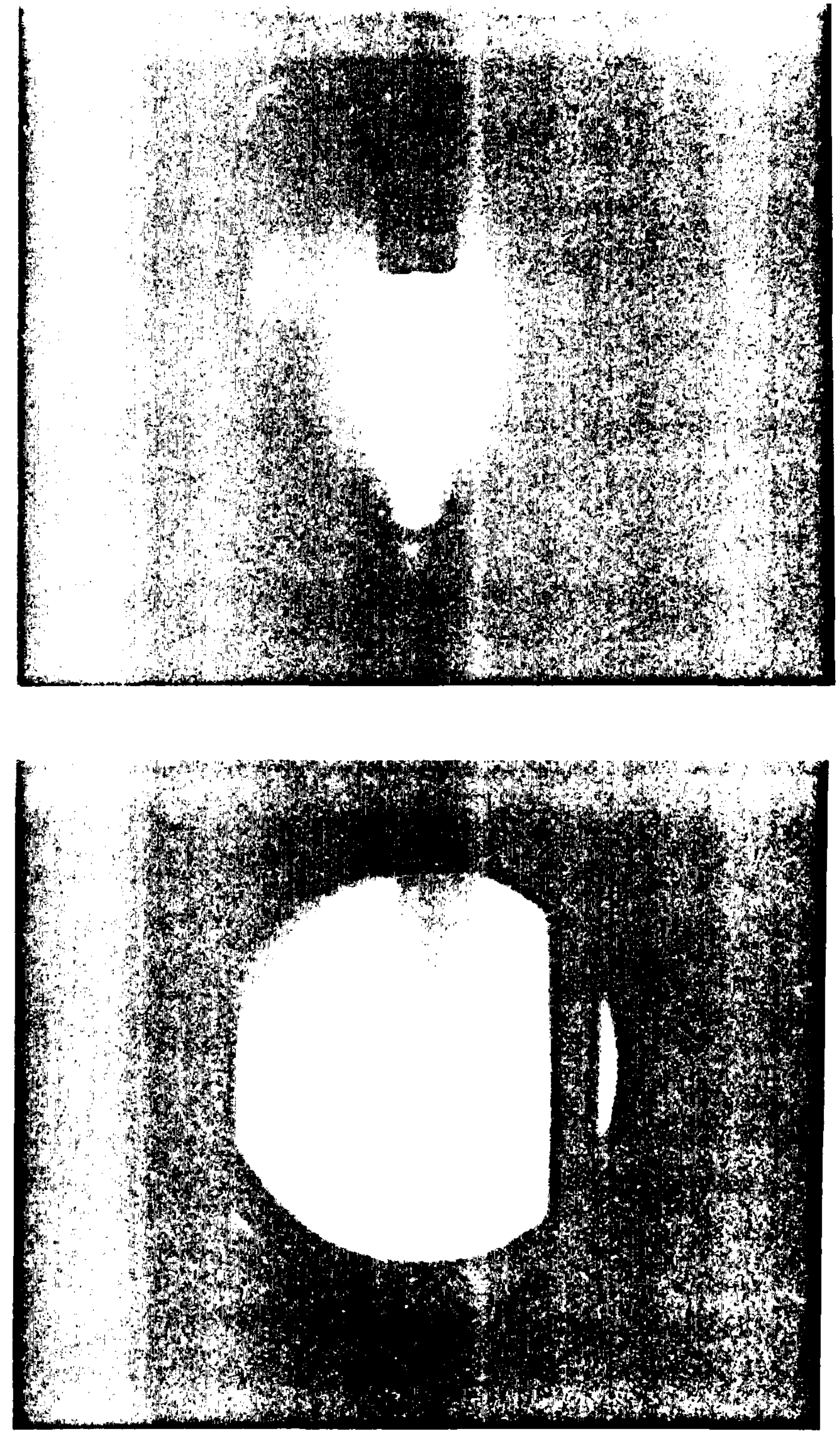


Fig. 14 Photograph of (a) the high current "vacuum"-discharge and (b) the low current electron beam discharge. Magnetic fields applied in the indicated direction changed the discharge resistance in the "electron-beam" mode.

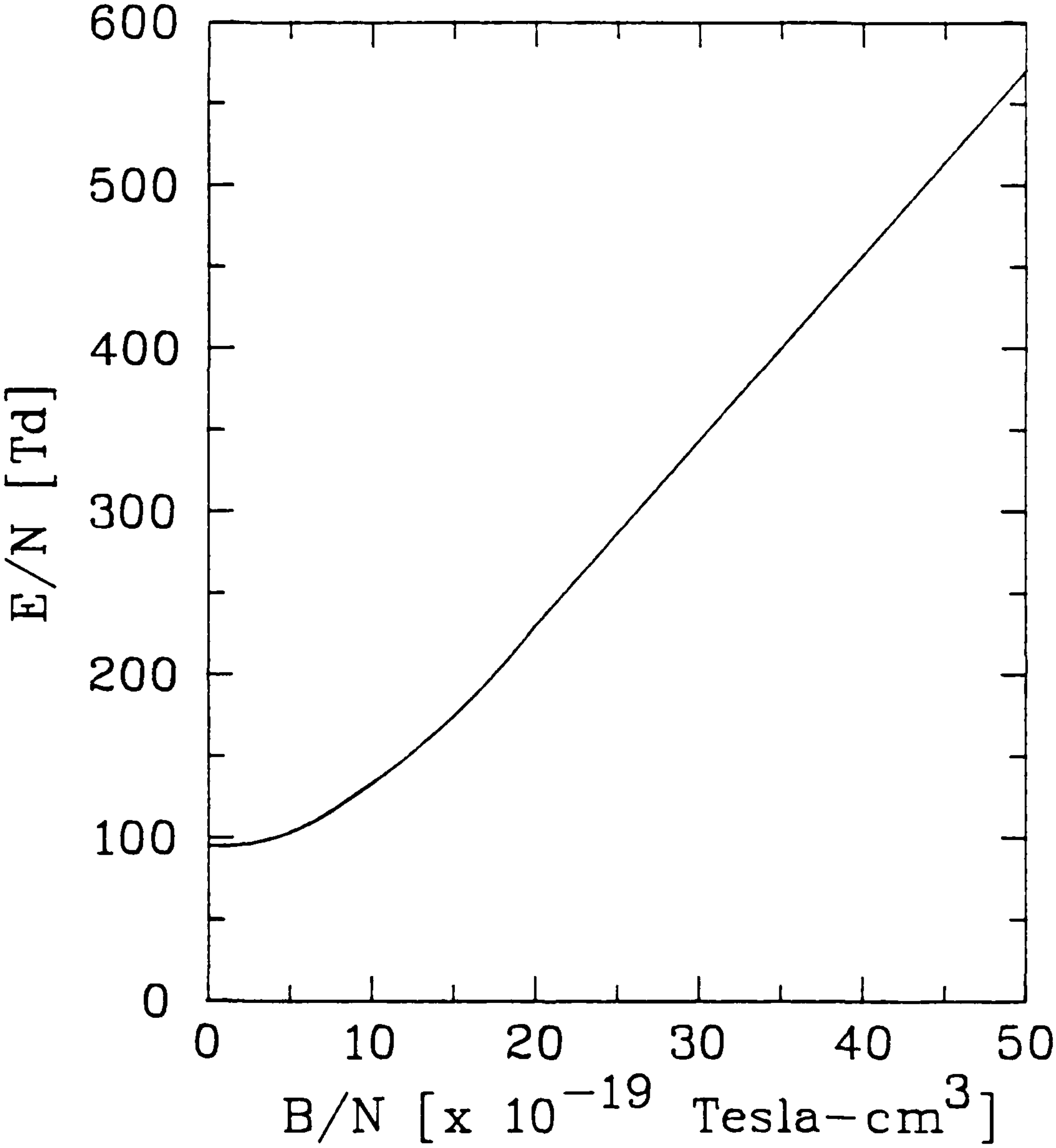


Fig. 15 Calculated reduced electric field intensity as a function of reduced magnetic field intensity. p = 10 torr, 20% SF_6 - 80% He.

20% SF_6 - 80% He. Except for small values of B/N, the E/N versus B/N curve increase linearly with a slope of about E/B - 1 kV/cm Tesla.

Details of the computational procedure and results of the calculations (rate coefficients, drift velocity) are discussed in the previous annual report and in the attached papers (Appendix).

B. CATHODE FALL

In order to model the cathode fall, which for abnormal discharges contributes substantially to the total discharge voltage, a one dimensional Monte-Carlo code was used. With this code the electron energy distributions and the transport and rate coefficients in the cathode fall region of glow discharges in a He/SF_6 gas mixture were calculated. The charge carrier densities and the current densities were computed by means of a continuum model. A self consistent solution for the cathode fall was approached through an iterative procedure. The modeling procedure and the obtained distribution of rate coefficients, charge densities and current is described in detail in the attached paper "Analysis of the Cathode Fall of Glow Discharges in a He:SF_6 Gas Mixture" [9].

Figure 16 shows the calculated spatial electric field distributions for zero magnetic field and a magnetic field of 0.5 Tesla with an assumed current density of 1 A/cm^2. The electric field for B=0 is linear except for the region adjacent to the positive column (negative glow). The cathode fall distance is very short compared to the cathode fall distance measured for normal cathode falls and the electric field intensity is correspondingly high. It reaches 35 kV/cm at the cathode. Application of a magnetic field of 0.5 Tesla causes a reduction of the electric field intensity in the cathode fall contrary to its effect in the positive column. The cathode

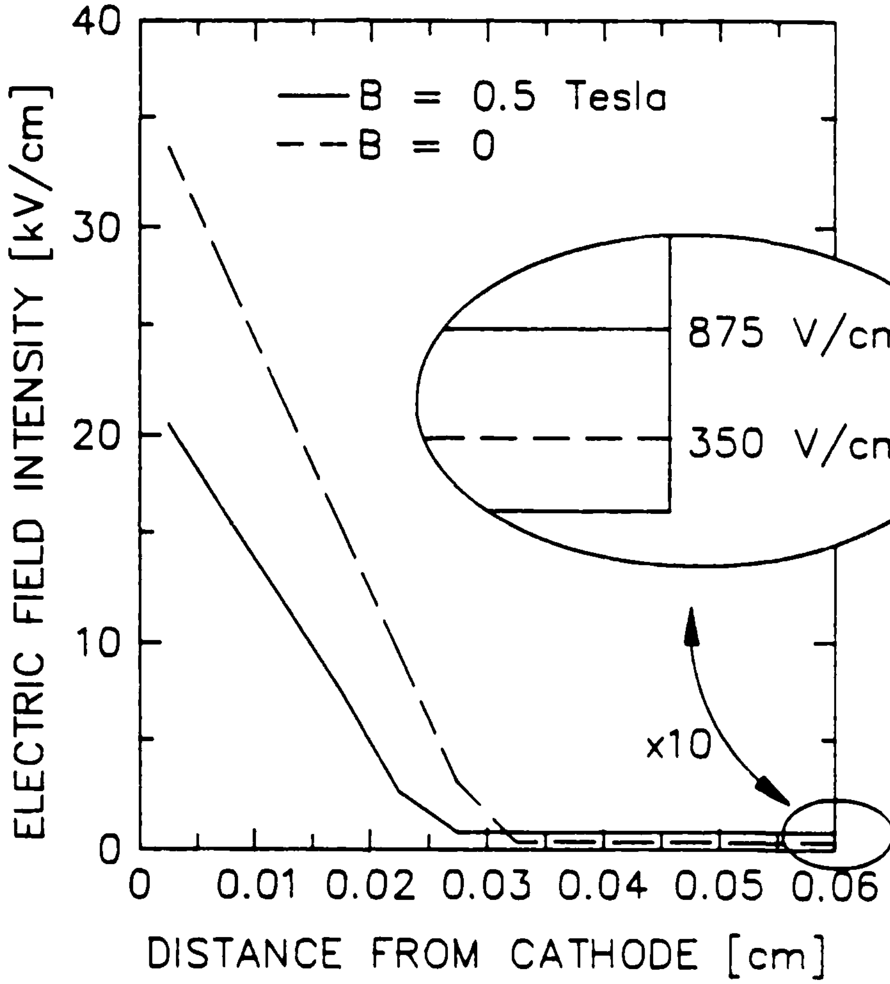


Fig. 16 Calculated electric field intensity as a function of distance from the cathode. p = 10 torr, 20% SF_6 - 80% He, J = 1 A/cm^2, B = 0 and B = 0.5 Tesla.

fall voltage is reduced to about 250 V, as compared to the value of 500 V for the cathode fall in the magnetic field free case.

DISCUSSION AND CONCLUSION

The computational results for positive column and cathode fall are shown in Fig. 17, compared with the experimental results, obtained in a $He:SF_6$ gas mixture at 8 Torr. The experimental data and the theoretical results are in relative good agreement for values of the magnetic field up to 0.5 Tesla. For higher values of magnetic field the measured rise of voltage with increasing magnetic field exceeds the computed one. This discrepancy between theory and experiment might be due to the fact that neither recombination nor diffusion was considered in our rate equations. Both mechanisms cause a reduction of electron density, consequently an increase in discharge potential and therefore a steeper slope in the computed E/N versus B curve.

The results of the measurements with transient magnetic fields indicate, that the relaxation time (turn-off time) is small compared to one microsecond, which is the characteristic time of change in the magnetic field used in this experiment. This is consistent with computational results on the temporal change of the electron energy distribution function, where decay time constants for the electron density in the order of 100 ns were calculated (Paper on "The Influence of Transverse Magnetic Fields on Glow Discharges in $He:SF_6$ Gas Mixtures," Appendix). The main problem related to fast (submicrosecond) switching, however, is not the relaxation of the electron energy distribution, but the induction of electric fields by the fast rising magnetic field, which cause a glow-to-arc transition before the opening effect sets in.

In order to use this device as a switch the current density should be larger than 1 A/cm^2 and the forward voltage should be relatively low. With simple brass electrodes and no preionization the experimental set-up

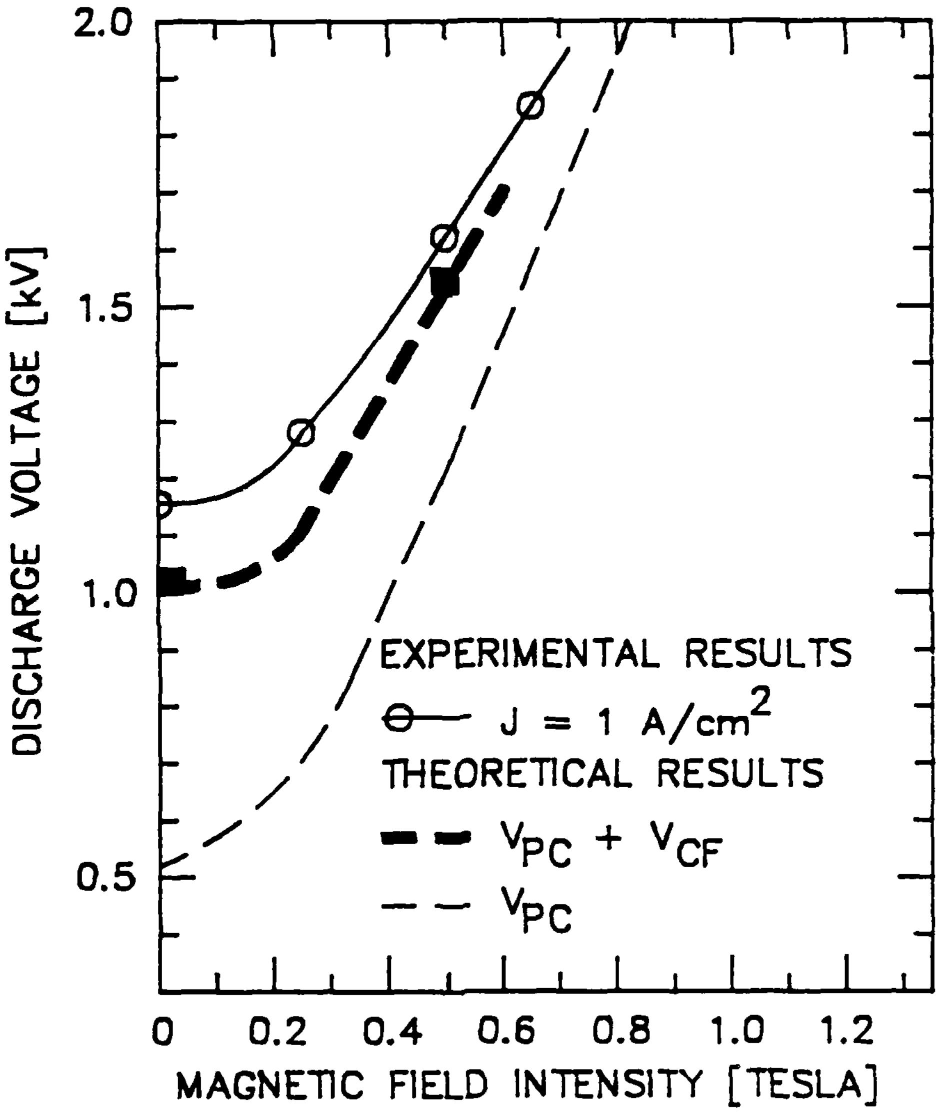


Fig. 17 Comparison of different discharge potential components derived from Monte-Carlo calculations to experimental results as a function of magnetic field intensity. V_{PC} is the positive column potential and V_{CF} is the cathode fall potential.

delivered current densities of up to 2 A/cm^2. One method to increase the current density is the use of a hollow cathode. When using such a cathode in the experimental set-up current densities ten times that obtained with the plane cylindrical cathode were obtained at approximately half the forward potential. Work done at GTE Labs Inc. indicates that current densities of several hundred amperes per square centimeter can be obtained when the gas is preionized [16].

The efficiency or gain of magnetically controlled opening switch can be defined as the ratio of power delivered by the switch to the load divided by the magnetic power required to operate the switch [7]:

$$G = \frac{\frac{1}{2}(JE)}{\frac{d}{dt}\left(\frac{1}{2}B^2/\mu\right)} = \frac{JE}{B^2/\mu r}$$

If the magnetic field intensity, B, rising from zero to 0.5 Tesla in a time τ, would generate an electric field, E, of 0.5 kV/cm_r then, the opening time, τ, required to get a gain greater than unity would have to be longer than 4 μs. The discussed magnetically controlled switch would therefore be suitable for opening a circuit in the 100 μs range with reasonable efficiency. The current could be scaled with the discharge cross section and the voltage with the length of the positive column.

WORK STATEMENT FOR THE 3RD CONTRACT PERIOD:

1. It is planned to perform electrical measurements (voltage and current) on pulsed, single hole and multi hole hollow cathode discharges in He using a recently built discharge system. The purpose of these measurements is to get information on the current-voltage characteristics, and stability of these discharges (with respect to their application as pulse power switches).
2. It is planned to study the influence of magnetic fields along the axis of the discharge on the sustaining voltage. The purpose of these experiments is to define ranges of operation where the application of magnetic fields leads to a reduction or an increase in discharge impedance (opening or closing switch). If it is possible to switch between different modes of operation (Fig. 13), resistance changes by four orders of magnitude can be expected.
3. It is planned to expand our one-dimensional boundary layer model, which uses Monte-Carlo codes to determine the rate coefficients and electron drift velocity under nonequilibrium conditions, into a two-dimensional model. This will allow to model hollow cathode discharges. For the development of the two-dimensional code, we have the support of S. Taasan, an expert on numerical solutions of Partial Differental Equations (NASA Langley).

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APPENDICES

APPENDIX A

Magnetic Control of Diffuse Discharges, IEEE Transactions on Plasma Science, Vol. PS-14, No. 4, August 1986.

Magnetic Control of Diffuse Discharges

J. R. COOPER, MEMBER, IEEE, KARL H. SCHOENBACH, SENIOR MEMBER, IEEE, AND G. SCHAEFER, SENIOR MEMBER, IEEE

***Abstract*—By application of a crossed magnetic field, the electron energy distribution in a gas discharge can be shifted to lower energy values, as demonstrated by means of Monte Carlo calculations for electrons in He:SF_6 mixtures. Consequently, through the change in the rate coefficients for ionization and attachment, the sustaining field in the discharge plasma is increased. This magnetically induced voltage rise was studied in a low-pressure glow discharge. The cathode fall was found to be the dominant component in determining the characteristics of this magnetically controlled discharge. The drastic rise of the cathode fall above a threshold value could be utilized in operating a glow discharge as an opening switch for an inductive energy storage system.**

I. Introduction

LOW-PRESSURE diffuse discharges have been studied extensively with respect to their application as closing switches. Examples of switching devices operating at low pressures are thyratrons [1], tacitrons [2], and crossatrons [3]. Common to all these devices is their operation on the low *pd* side of the Paschen minimum, with *p* being the gas pressure and *d* the electrode spacing. The application of crossed magnetic fields in this *pd* range leads to a decrease in breakdown strength and plasma resistivity in the on state of a switch, an effect which has been successfully used in operating crossed field tubes as closing switches.

If the gas pressure is such that *pd* is on the high side of the Paschen minimum, the application of a crossed magnetic field has the opposite effect. In this *pd* range, where the characteristic of the discharge is determined by electron–molecule collisions, rather than by electrode (γ) processes, the applied magnetic field causes a change in the transport properties of the discharge such that an increase in both breakdown field strength [4] and resistivity [5] occurs. This effect provides a means for the use of magnetically controlled low-pressure discharges as opening switches.

II. Theory and Computational Results

The application of a magnetic flux density $\vec{B}$, which is transverse to the electric field $\vec{E}$ in the discharge, changes the transport parameters of the electrons by changing the electron energy distribution $f(\epsilon)$. This was demonstrated by means of Monte Carlo calculations in pure SF_6. Fig. 1 illustrates this shift in the distribution function for a mixture of He and SF_6. These data were generated again by Monte Carlo calculations [7]. The cross sections for this calculation for He were taken from a paper by Hayashi [8] and those for SF_6 were taken from Kline [9]. The electron scattering was assumed to be isotropic. The major points of interest in the crossed field induced changes in $f(\epsilon)$ are the reduction in the high-energy tail of the distribution and the shift of the mean energy to lower values with increasing reduced magnetic flux density B/N, N being the number density of the gas molecules. The mean energies for the $B/N = 0$ and $B/N = 1.5 \times 10^{-18}$ T · cm^3 distributions are 11.6 and 8.0 eV, respectively.

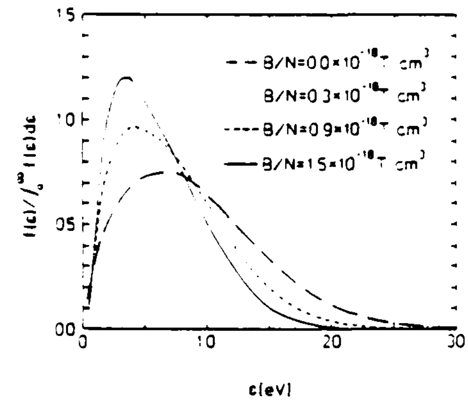

Fig. 1. Electron energy distributions for a reduced electric-field strength of E/N = 120 Td in 20-percent SF_6-80-percent He for various values of reduced magnetic flux density B/N.

The effect on the tail of $f(\epsilon)$ can be explained by considering the electron trajectories in crossed electric and magnetic fields. The electrons that make up the high-energy part of the electron energy distribution in a gas with an electric field only are those which have been forward scattered, i.e., scattered in the direction of the electric field lines. The forward-scattered electrons in a crossed field discharge travel paths that are curved due to the $\vec{v} \times \vec{B}$ forces acting on the particle. This means that forward-scattered electrons will not gain as much energy as in the "electric-field-only" case, so the high-energy tail of the electron energy distribution is reduced. The shift in the mean energy has been derived both analytically [10] and in computer simulations [5], [11] for crossed field discharges.

The changes in the distribution function significantly affect the electron transport parameters of a discharge in

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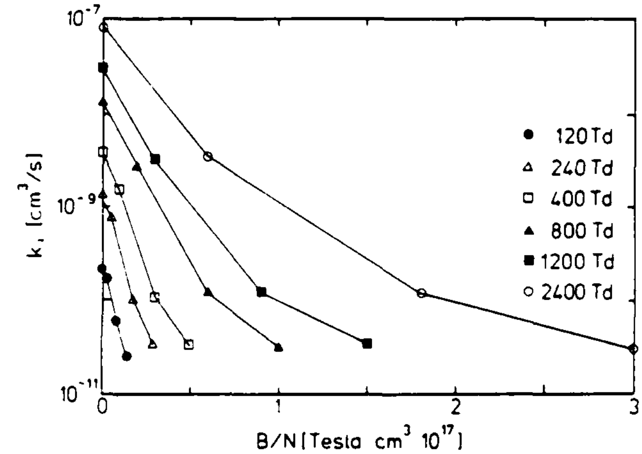

Fig. 2. Ionization rate coefficient k_i as a function of reduced magnetic flux density B/N with the reduced electric field strength E/N as a parameter in 20-percent SF_6–80-percent He.

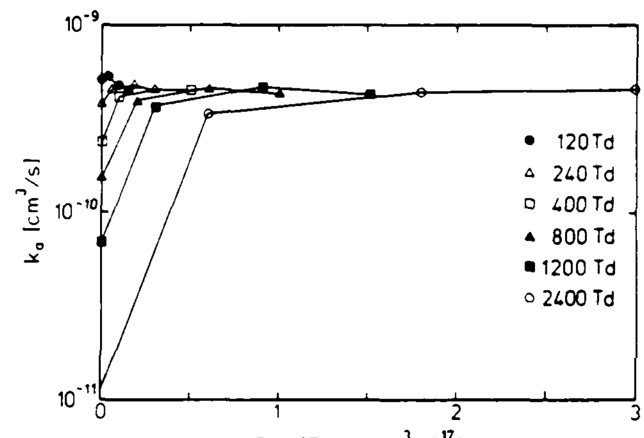

Fig. 3. Attachment rate coefficient k_a as a function of reduced magnetic flux density B/N with the reduced electric field strength E/N as a parameter in 20-percent SF_6–80-percent He.

a gas mixture of 20-percent SF_6 and 80-percent He, as shown by the plots of ionization and attachment rate coefficients in Figs. 2 and 3, respectively. These data were generated by counting the number of ionization and attachment processes with the same Monte Carlo calculations as were used to produce the distribution functions of Fig. 1. Rate coefficients in a gas are defined by the equation

$$k_j = \sqrt{\frac{2}{m_e}} \int \sigma_j(\epsilon)\, \epsilon^{1/2} f(\epsilon) d\epsilon \qquad (1)$$

where k_j is the rate coefficient, $\sigma_j(\epsilon)$ is the corresponding collision cross section, m_e is the electron mass, and ϵ is the electron energy. In Fig. 2 it can be seen that the ionization rate coefficient k_i is reduced by more than three orders of magnitude by the application of a magnetic field of $B/N = 1.5 \times 10^{-18}$ T · cm³ for 20-percent SF_6 and 80-percent He. The attachment rate coefficient k_a is strongly affected by the magnetic field only below some threshold value. For E/N = 2400 Td, this threshold is at $B/N = 6 \times 10^{-18}$ T · cm³, as shown in Fig. 3. The rate

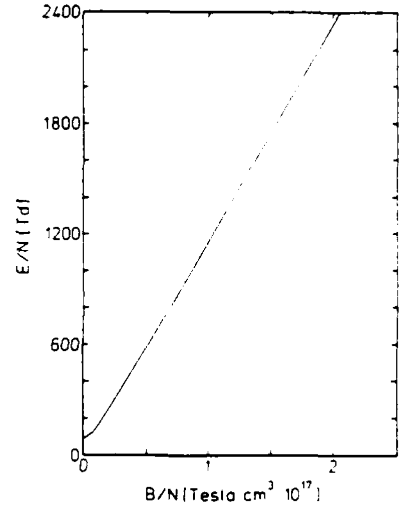

Fig. 4. Calculated positive column equilibrium reduced electric field strength E/N versus reduced magnetic flux density B/N for 20-percent SF_6–80-percent He.

coefficient remains fairly constant above this value of B/N. This behavior is typical for an attacher whose attachment cross section peaks at low energies, such as SF_6 [9]. The drift velocity v_d for a particular E/N is also reduced if a transverse magnetic field is present. This is due to the lowered electron mobility in the electric-field direction caused by the gyrating path of the electrons in crossed fields.

The computed rate coefficients k_i and k_a can be used in the continuity equation for electrons to calculate the equilibrium E/N for the positive column of a discharge plasma as a function of B/N. This equilibrium E/N, or limiting E/N, is the electric-field intensity at which

$$dn_e/dt = k_i N n_e - k_a N_a n_e = 0. \qquad (2)$$

The results from such a calculation for a 20-percent SF_6–80-percent He gas mixture are shown in Fig. 4. Except for small values of B/N ($<0.1 \times 10^{-17}$ T · cm³), the E/N versus B/N curve increases linearly with a slope of $E/B \sim 1$ kV/(T · cm).

III. Experimental Results

Experimental studies of low-pressure glow discharges in crossed electric and magnetic fields were performed with the apparatus shown in Fig. 5. The discharge is produced by overvolting a coaxial gap whose dc breakdown voltage in 8 torr of 20-percent SF_6–80-percent He is approximately 2 kV. The brass center conductor is the cathode, which has a diameter of 3.18 cm and a surface area of 100 cm². The anode is a set of twelve 0.32-cm-diameter stainless steel rods arranged to form a cylinder around the cathode. The anode–cathode gap spacing is 2.06 cm at the minimum point. The spacing between the rods allows the magnetic field to permeate the discharge with a time constant determined by the plasma conductivity. The discharge can be driven by either a 50-Ω 1-μs pulse-form-

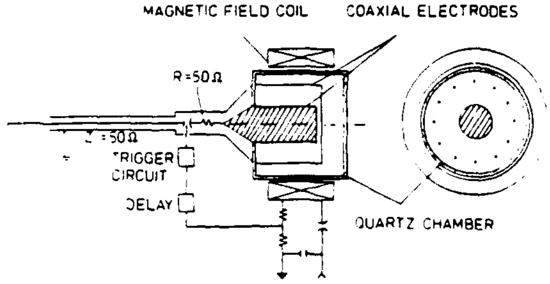

Fig. 5. Experimental apparatus.

ing network (PFN) or by a section of 50-Ω cable and is switched by a midplane triggered spark gap using a krytron trigger circuit. The discharge system, which is matched to 50 Ω, is designed to deliver voltage pulses of up to 40 kV to the discharge chamber with rise times on the order of nanoseconds.

The magnetic field is applied axially to the discharge chamber by a coil which is driven by a 20-kV capacitor bank. The total capacitance of this bank is 45 μF, the inductance of the magnetic-field coil, which is wound on a form and placed around the discharge chamber, is 970 μH, and the circuit is overdamped to prevent voltage reversals on the capacitors. The current is switched to the coil through a spark gap. Magnetic flux densities of up to 0.8 T can be obtained with this circuit. The time scale of the pulse is such that the magnetic field strength is constant for the duration of the glow discharge. Timing for the system is accomplished by picking off a portion of the magnetic-field coil current to trigger a delay generator which in turn fires the krytron trigger pulser and initiates the discharge. The delay can be adjusted so that the discharge occurs during the time when the magnetic flux density is at its desired level. The discharge current was measured with a Rogowski coil, and the total discharge voltage was calculated using this measured current and transmission line data.

The effect of the magnetic field on the discharge impedance is strongly dependent on the pressure range where the discharge is operated. Results of impedance measurements with and without magnetic field over a pressure range from 0.5 to 7 torr are shown in Fig. 6. Below 5 torr, the application of a magnetic field causes the impedance to drop, a fact which is utilized in crossed field tubes [3]. Above approximately 5 torr, the discharge characteristics are determined by electron-molecule collisions as discussed previously. In this range, the impedance increases in crossed field configurations. Experiments attempted with a magnetic field at higher values of B/N lead to filamentary discharges with onset times on a nanosecond time scale.

The equilibrium voltage of the glow discharge with varying magnetic fields at a pressure of 8 torr in a 20-percent SF_6–80-percent He gas mixture is given in Fig. 7. The discharge current in this experiment was on the order of 150 A. The measured discharge voltage shows a linear increase with a slope of approximately 6 kV/T up

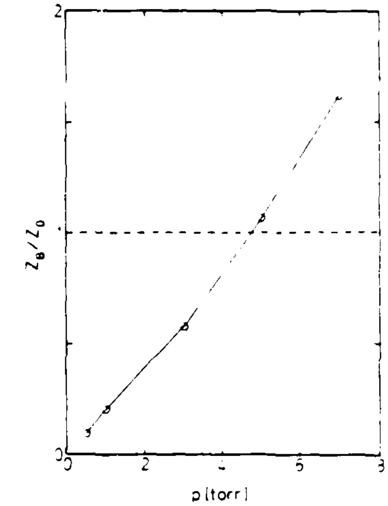

Fig. 6. Discharge impedance with magnetic field Z_B normalized to discharge impedance without magnetic field Z_0 as a function of gas pressure p for 20-percent SF_6–80-percent He and $B = 0.2$ T. The circles are the experimental points.

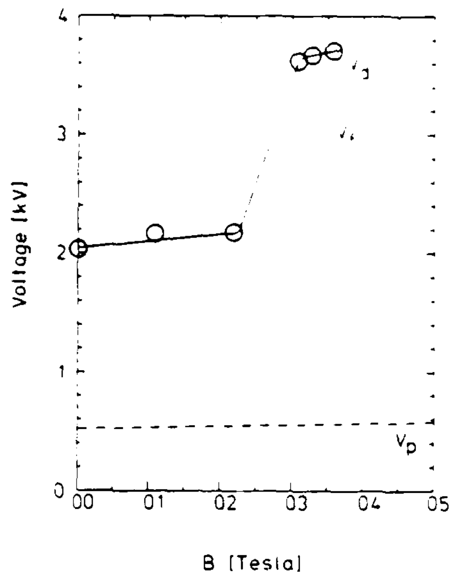

Fig. 7. Discharge voltage V_d, calculated positive column voltage V_p, and derived electrode fall voltage V_c as a function of magnetic flux density B for 20-percent SF_6–80-percent He at $p = 8$ torr. The circles are the experimental points.

to 0.02 T. Above this value of B, the voltage rises sharply with a slope on the order of 100 kV/T. At values above 4 kV further measurements were not possible due to the increasingly rapid glow-to-arc transitions at higher voltages, which lead to a sudden drop in discharge impedance.

Comparing the experimental values with computational results allows estimation of the cathode voltage drop in the glow discharge. We have assumed that the positive column extends over the entire distance between the electrodes and that E/N is constant in this region. Using the computed equilibrium values of the reduced electric field strength, the positive column shows a magnetic-field dependence, as shown in Fig. 7. The difference between the

measured voltage and the positive column voltage is the sum of the anode and cathode fall voltages. The cathode fall is typically the much larger of the two under the conditions of the experiment. Under these assumptions, the calculated cathode fall was found to be constant up to $B \sim 0.02$ T. Above this value it rises drastically, with a slope of approximately 100 kV/T. That means that above a certain magnetic field strength the total voltage seems to be primarily determined by fall processes for the range studied experimentally.

IV. Discussion

From the computationally obtained values for the voltage drop across the positive column and the total discharge voltage, it is apparent that the cathode fall region strongly influences the discharge characteristics, both with and without an applied magnetic field. For $B = 0$, the cathode fall was found to be 1.5 kV, which is almost an order of magnitude higher than the values normally reported [12], [13]. This high value is typical for abnormal glow discharges, i.e., glow discharges whose current is so high that the current density at the cathode is determined by the area of the cathode rather than the external circuit parameters. Studies by von Engel [11] show that the abnormal cathode fall voltage is an increasing function of j_c/p^2, where j_c is the current density at the cathode and p is the gas pressure. This means that for abnormal glows the discharge is in a range of operation in which the V–I characteristic has a positive slope. For our experimental values, $I \sim 150$ A, cathode area $A_c = 100$ cm^2, and $p = 8$ torr, the value for j_c/p^2 falls well into the region of abnormal glow discharges for He [11]. Since the presence of SF_6 in the gas mixture contributes to the properties of the cathode fall as well, direct comparison to the von Engel data is not possible.

For $B \neq 0$, there is a sharp increase in voltage above a threshold value of $B = 0.02$ T. A qualitative understanding of the strong magnetic-field dependence of the cathode voltage can be gained by observing the characteristics of the electron energy distribution of the cathode fall at $B = 0$. The electron energy distribution in the cathode fall in a normal glow at the edge of the negative glow region has been calculated by An *et al.* [14]. Their results show that a large number of electrons produced at the cathode do not collide in the cathode fall region, so that there is a peak in the distribution at an energy corresponding to the full cathode fall voltage. The characteristics of the electron energy distribution of an abnormal glow cathode fall should be similar except for the difference in energy caused by the higher cathode fall voltage. If a transverse magnetic field is applied, this high energy peak will be greatly reduced. In order to compensate for the resulting decrease in the ionization rate, the cathode fall voltage must increase.

If such a discharge is considered as a switch in an electric discharge circuit, the current will decrease with increasing magnetic field. This decrease in current will eventually turn the initially abnormal discharge into a normal one with reduced cathode fall. This means that at high magnetic field strengths the total hold-off voltage of the switch will be determined mainly by the voltage across the positive column, rather than the cathode fall.

Whereas the sharp increase in discharge voltage at a threshold B/N is a desirable effect for an opening switch, the increasingly rapid transition from glow to arc with higher magnetic fields could impose certain restraints to the use of a magnetically controlled discharge as a switch. However, if operated as an opening switch, in which the magnetic field is applied after the discharge is fully established, rather than before breakdown (as in our experiment), the device should exhibit reduced arcing compared to the results previously discussed. A way to improve the discharge further with respect to its application as a switch is to reduce the strong electric field in the cathode region during the conduction phase ($B = 0$). Two types of cathodes which could help to achieve this end are thermionic cathodes and hollow cathodes [15]. Both of these electrodes have the capability to produce high current densities while maintaining a lower forward voltage drop across the discharge.

The lower forward voltage drop not only aids in delaying the instabilities in the cathode region [16], but is also important for reduced power loading in the gas during conduction. The higher current density is necessary to achieve reasonable power gains in inductive energy storage systems with a magnetically controlled discharge as the opening switch. The power gain G can be defined as the power transferred into the load divided by the change in magnetic-field energy necessary to generate an electric field $\overline{E_{max}}$ averaged over the axis of the discharge. For a resistive load of resistivity $\overline{E_{max}}/J$, G is on the order of

$$G = \frac{\frac{1}{2}(J\,\overline{E_{max}})}{\frac{d}{dt}(B^2/2\mu_0)}. \tag{3}$$

Assuming that the discharge is biased at a static magnetic flux density B_0 just below the sharp increase in voltage with B (see Fig. 7), a drastic increase in electric field intensity can be obtained with rather moderate transient B fields on the order of 0.01 T. With opening times of approximately 0.1 μs, and electric field intensities of $E_{max} \sim 1$ kV/cm, current densities of $J > 1$ A/cm^2 are required to obtain power gains in excess of unity.

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APPENDIX B

Magnetic Control of Low Pressure Discharges

6th Pulsed Power Conference, Arlington, VA, June 1987

MAGNETIC CONTROL OF LOW-PRESSURE DISCHARGES*

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Abstract

The effect of a transverse magnetic field on the steady state characteristics of glow discharges in He-SF_6 gas mixtures was studied experimentally and theoretically. A coaxial discharge system was used which allows application of axial magnetic fields up to 1.2 Tesla. Measurements of the discharge voltage in a He-SF_6 mixture at a pressure of 3 Torr were performed at various magnetic field intensities. At current densities of 1 A/cm^2 and an interelectrode distance of 2 cm, the discharge voltage was found to increase with increasing magnetic field at a rate of [illegible] kV/Tesla. The experimental results were compared to the results obtained with a continuum model for the cathode fall and the positive column. The results of this study indicate that a magnetically controlled discharge may be used as an opening switch with opening times in the microsecond to millisecond range.

Introduction

The effects of a transverse magnetic field on a glow discharge have been studied since the late nineteenth century [1]. J.J. Thomson in his 1933 text states that application of a transverse magnetic field to the positive column increases the discharge potential. He further states that a transverse magnetic field decreases the discharge potential in the cathode fall region at lower pressures and increases it at higher pressures [2]. Most of the experimental work on the effect of magnetic fields on glow discharges has been done in systems which operate on the low pd side (left hand) of the sustaining voltage minimum, where p is the pressure and d is the electrode spacing. On the left hand side of the pd minimum the application of a transverse magnetic field decreases the discharge potential. This effect has been successfully used in closing and opening switches [3] and to reduce the forward potential of cold cathode tubes [4].

Very little work has been done on the high pd side of the voltage minimum. In this range the application of a transverse magnetic field increases the discharge potential [5,6] and the breakdown potential [7]. This effect is due to the shift of the electron energy distribution towards lower energy and the reduction of the high energy tail of the distribution in crossed electric and magnetic fields. To enhance this effect an attacher gas with a large attachment cross section at lower energies may be used. This is illustrated in figure 1. When the electron energy distribution shifts downward the electron energy mobility is reduced, the probability of attachment increases and the probability of ionization decreases. This effectively reduces the conductivity and helps to extinguish the discharge [8]. This effect provides a means for the use of magnetically controlled low-pressure discharges as opening switches.

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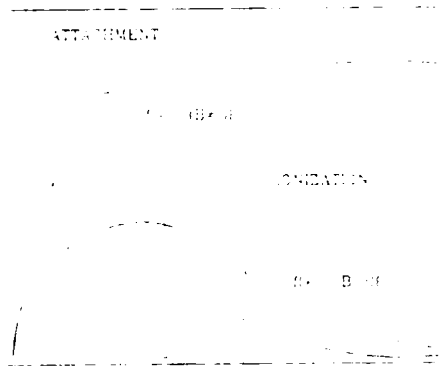

Fig. 1 An illustration of the concept of magnetic field control of diffuse discharges using an attacher gas.

Experimental Set-up

The experimental set-up consists of a coaxial discharge chamber surrounded by a solenoidally shaped coil. This allows the application of a "quasi-dc" axial magnetic field to a radial glow discharge, of current densities up to 2 A/cm^2. The experimental set-up has been described in reference [5]. The magnetic field circuit is a series RLC circuit capable of delivering peak currents of [illegible] kA which produced magnetic fields in excess of 1.2 Tesla. The discharge circuit consists of a [illegible] Ω cable and a mid-plane triggered spark gap which delivers a [illegible]00 ns pulse to a [illegible] Ω shielded resistor in series with the discharge chamber. In order to obtain longer pulses a 10 µs pulse forming network was also used.

Both the discharge voltage and current were recorded using transient digitizers and the magnetic field circuit current was recorded using a storage oscilloscope on every shot. The current waveforms were measured using commercial Rogowski coil current transformers. The discharge voltage was monitored by a capacitive voltage divider in series with a resistive voltage divider. This device has a fast risetime which is limited by the self inductance of the two carbon resistors in the resistive part of the divider. A cross-sectional view of the voltage divider is shown in figure 2. The step response of this device is an exponentially decaying signal which has a time constant equal to the product of the sum of the two resistors times the sum of the two capacitors. For short pulses (<60 ns) the voltage divider provides an accurate reproduction of the input signal. Longer signals must be processed digitally to compensate for this decay.

Figures 3a and 3b are plots of the voltage and current waveforms for four consecutive data points taken under the same conditions. The gas mixture was [illegible] SF_6 [illegible] % He and the applied magnetic field was [illegible] Tesla. The jitter in the original waveforms was removed by aligning three of the waveforms with the first using an interactive graphics program. The difference in the first 300 ns of the voltage waveforms is due the statistical delay of the discharge initiation.

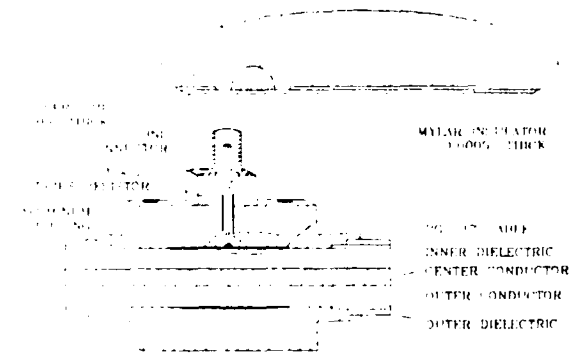

Fig.2 Isometric drawing of the capacitive voltage divider.

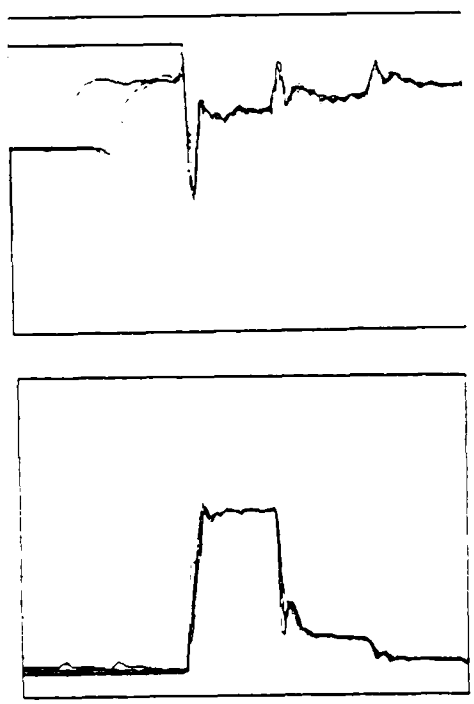

Fig 3 Typical discharge (a) voltage and (b) current waveforms showing four consecutive shots superimposed. 20% SF_6 - 80% He, B = 0.05 Tesla, 100 ns/div, (a) 618 V/div and (b) -15 A/div.

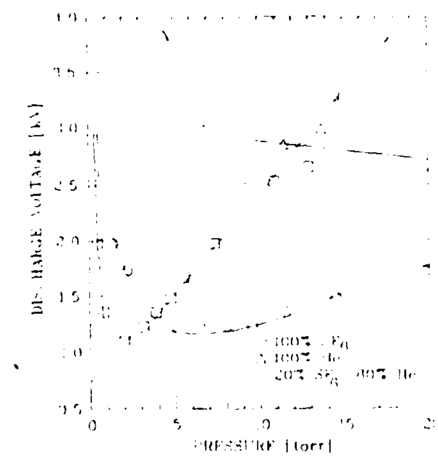

Fig. 4 Experimental values of discharge voltage as a function of gas pressure for various gases. Discharge current is 100 A.

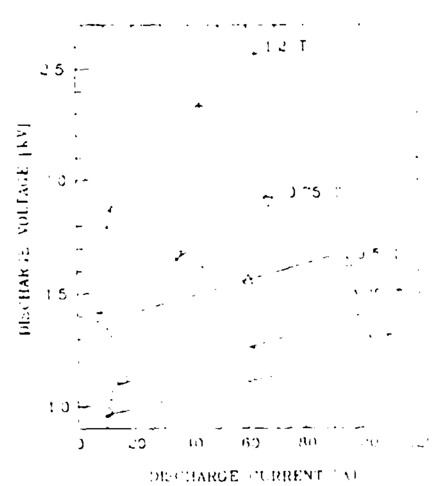

Fig. 5 Experimental values of discharge voltage as a function of discharge current in an 80% He - 20% SF_6 gas mixture at 8 torr for various values of applied transverse magnetic field intensity.

Experimental Results

To determine the operating pressure of the gas in the discharge chamber, pressure versus discharge voltage data were taken. Figure 4 shows the measured values of pressure versus sustaining voltage for a current density of 1 A/cm^2 in SF_6, He and an 80% He - 20% SF_6 mixture. While these curves should not be confused with Paschen curves (which are pd versus sparking voltage), the curves for SF_6 and the SF_6 He mixture show the typical Paschen curve shape. There is a minimum voltage which increases as the pressure is either increased or decreased. The minimum voltage for SF_6 and the SF_6/He mixture are 1100 V and 1200 V respectively. The He curve has its minimum at a pressure greater than 20 torr.

Figure 5 is the measured quasi steady-state voltage current characteristics for the discharge with applied transverse magnetic field. These measurements were made using a 20% SF_6 - 80% He gas mixture at a pressure of 8 torr. The measurements were made by recording both the discharge current and voltage waveforms for several values of applied voltage at specific values of magnetic field intensity. Several data points were taken for each value of applied voltage.

The relationship between the discharge voltage and the applied magnetic field strength at constant discharge current was determined from figure 5. These data are given as figure 6 for discharge currents of 20 A, 60 A and 100 A. With a cathode surface area of 100 cm^2, the corresponding current densities were 0.2 A/cm^2, 0.6 A/cm^2 and 1.0 A/cm^2 respectively. The plot shows an initial increase in discharge voltage with respect to magnetic field (dV/dB) of approximately 0.4 kV/Tesla for the three

values of current. This increases to a steady value which is dependent on the discharge current. The final values of dV/dB for the three values of current are listed below.

I	dV/dB	B
20 A	1.6 kV/Tesla	0.5 < B < 1.2 Tesla
60 A	2.3 kV/Tesla	0.6 < B < 1.2 Tesla
100 A	2.6 kV/Tesla	0.5 < B < 0.65 Tesla

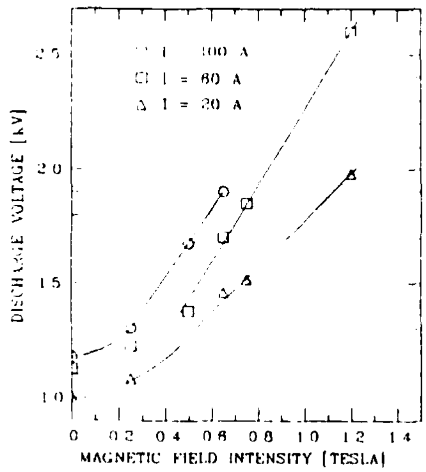

Fig. 6 Experimental values of discharge voltage as a function of applied transverse magnetic field intensity in an 80% He - 20% SF_6 gas mixture at 8 torr for various values of discharge current.

Computational Results

Monte-Carlo calculations were performed to simulate the positive column and the cathode fall of glow discharges in transverse magnetic fields. The gas mixture, which was chosen for our studies, was 20% SF_6 - 80% He at a pressure of 10 torr. SF_6-data compiled by Kline [9] and Phelps [10] were used. The cross sections for He, which serves as buffer gas, were taken from a paper by Hayashi [11].

A zero dimensional Monte-Carlo code was used to calculate the electron-energy distribution, ionization rate coefficient, attachment rate coefficient, collision frequency and drift velocity in the positive column [12,13]. The computed attachment and ionization rate coefficients were used in a simplified continuity equation for electrons, where detachment, recombination and diffusion processes are neglected. This equation resulted in the calculation of the equilibrium reduced field strength, E/N, for the positive column of a discharge plasma as a function of the reduced magnetic field intensity, B/N. The results from such calculations are shown in figure 7 for 20% SF_6 - 80% He. Except for small values of B/N, the E/N versus B/N curve increase linearly with a slope of about E/B = 1 kV/cm·Tesla.

In order to model the cathode fall, which for abnormal discharges contributes substantially to the total discharge voltage, a one dimensional Monte-Carlo code was used. With this code the electron energy distributions and the transport and rate coefficients in the cathode fall region of glow discharges in a He/SF_6 gas mixture were calculated. The charge carrier densities and the current densities were computed by means of a continuum model. A self consistent solution for the cathode fall was approached through an iterative procedure. The modeling procedure and the obtained distribution of rate coefficients, charge densities and current is described in detail in reference [13].

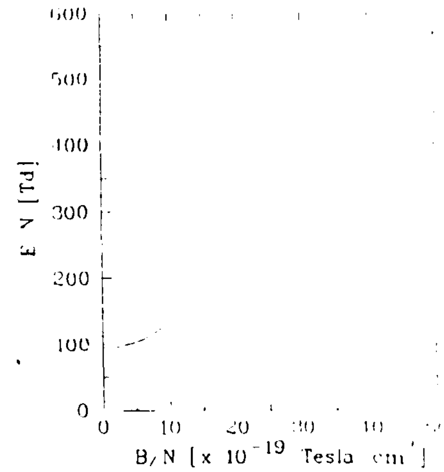

Fig. 7 Calculated reduced electric field intensity as a function of reduced magnetic field intensity. p = 10 torr, 20% SF_6 - 80% He

Figure 8 shows the calculated electric field distributions for zero magnetic field and a magnetic field of 0.5 Tesla with an assumed current density of 1 A/cm^2. The electric field for B=0 is linear except for the region adjacent to the positive column (negative glow). The cathode fall distance is very short compared to the cathode fall distance measured for normal cathode falls and the electric field intensity is correspondingly high. It reaches 35 kV/cm at the cathode. Application of a magnetic field of 0.5 Tesla causes a reduction of the electric field intensity in the cathode fall contrary to its effect in the positive column. The cathode fall voltage is reduced to about 250 V, as compared to the value of 500 V for the cathode fall in the magnetic field free case.

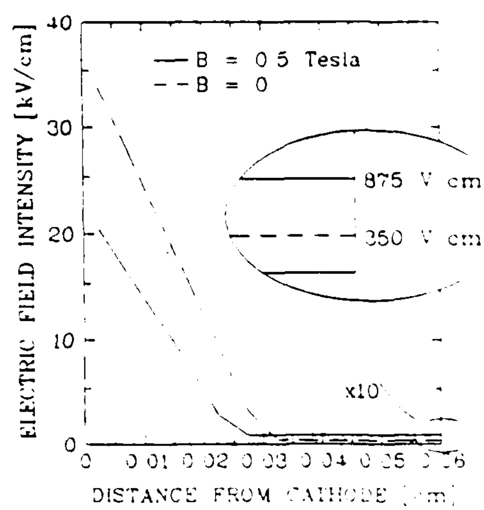

Fig. 8 Calculated electric field intensity as a function of distance from the cathode. p = 10 torr, 20% SF_6 - 80% He, J = 1 A/cm^2, B = 0 and B = 0.5 Tesla

Discussion

In figure 9 the theoretical results for the positive column and the cathode fall of a discharge in a 20% SF_6 - 80% He gas mixture are compared to the experimental values. In general, the experimental data and theoretical results appear to be in agreement for values of magnetic field up to 0.5 Tesla. At higher values of magnetic field, the rate of rise of voltage with respect to magnetic field intensity determined by the Monte-Carlo method (1.8 kV/Tesla) falls between the experimental values for 0.2 A/cm^2 (1.6 kV/Tesla) and 0.6 A/cm^2 (2.3 kV/Tesla). This discrepancy between theory and experiment might be due to the fact that recombination was not considered in the rate equation which was used. Recombination causes a reduction of the electron density and therefore an increase in the electric field strength for the same current density.

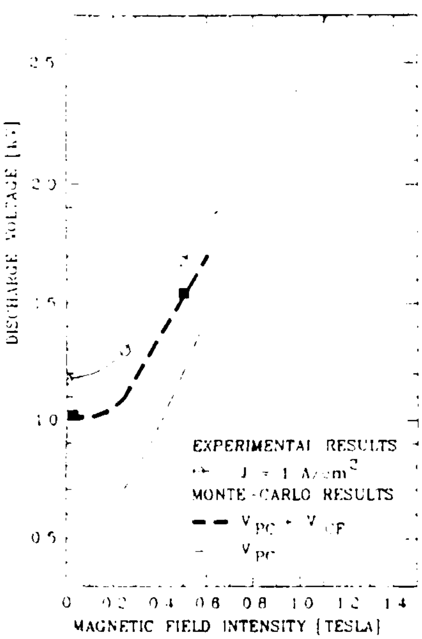

Fig. 9 Comparison of different discharge potential components derived from Monte-Carlo calculations to experimental results as a function of magnetic field intensity. V_{PC} is the positive column potential, and V_{CF} is the cathode fall potential.

In order to use this device as a switch the current density should be larger than 1 A/cm^2 and the forward voltage should be relatively low. With simple brass electrodes and no preionization the experimental set-up delivered current densities of 2 A/cm^2. One method to increase the current density is the use of a hollow cathode. When using such a cathode in the experimental set-up current densities ten times that obtained with the plane cylindrical cathode were obtained at approximately half the forward potential. Work done at GTE Labs Inc indicates that current densities of several hundred amperes per square centimeter can be obtained when the gas is preionized [14].

The efficiency or gain of a magnetically controlled opening switch can be defined as the ratio of power delivered by the switch to the load divided by the magnetic power required to operate the switch [12].

$$G = \frac{\frac{1}{2}(JE)}{\frac{d}{dt}\left(\frac{1}{2}B^2/\mu\right)} \approx \frac{JE}{B^2/\mu\tau}$$

If the magnetic field intensity, B, rising from zero to 0.5 tesla in a time τ, would generate an electric field, E, of 0.5 kV/cm in the discharge for a current density of 100 A/cm^2. The opening time, τ, required to get a gain greater than unity would then have to be greater than 4 μs. The discussed magnetically controlled switch would therefore be suitable for opening a circuit in the 100 μs to millisecond range. The current could be scaled with the discharge cross section and the voltage with the length of the positive column.

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APPENDIX C

The Influence of Transverse Magnetic Fields on Glow Discharges in He/SF_6 Gas Mixtures

5th Symposium on Gaseous Dielectrics, Knoxville, TN, May 1987

THE INFLUENCE OF TRANSVERSE MAGNETIC FIELDS ON GLOW DISCHARGES IN He/SF_6 GAS MIXTURES

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ABSTRACT

The application of a magnetic field transverse to the electric field in an ionized gas causes a shift in the electron energy distribution towards lower energies. This shift affects the transport and rate coefficients, and consequently the resistivity of the ionized gas. This effect could be utilized to modify the resistance of glow discharges and to use them for high power switching. In order to model the positive column of glow discharges in He/SF_6 gas mixtures, Monte-Carlo codes were used to determine the rate and transport coefficients. With the obtained values the current density - electric field characteristics of the positive column were computed. Besides steady state characteristics, the transient dynamic response of the discharge due to changes of the transverse magnetic field was studied. To investigate glow discharges in magnetic fields experimentally, a coaxial discharge system was used which allows application of axial magnetic fields up to 1.2 Tesla. Measurements of the discharge voltage and current in a 80% He/20% SF_6 mixture at a pressure of 8 torr were performed at varying magnetic field intensities. The discharge voltage was found to increase with increasing magnetic field as predicted by our model.

KEYWORDS

Glow discharge; SF_6; magnetic field; opening switch.

INTRODUCTION

Glow discharges are spatially characterized by four regions: the cathode fall, the negative glow, the positive column, and the anode fall. The cathode fall voltage, V_c, is for large current densities ($j > 1$ A/cm^2) on the order of kilovolts over a distance of typically less than one millimeter (von Engel, 1983). Voltages across the negative glow and the anode fall are negligible. The voltage drop in the positive column, where the electric field strength E is constant, is dependent on the length of the column. Control of the glow discharge through magnetic control of the positive column requires generally discharges with electrode distance, d, large compared to the cathode fall distance. Since this part of the discharge can be considered as a homogeneous plasma, a condition which allows to use zero order codes for modelling, theoretical studies concentrated initially on magnetic control of rate and transport properties in the positive column.

The conductivity in the positive column is given by the product of electron density, n_e, and electron mobility, μ_e, with ion contributions neglected. Both quantities are affected by the magnetic field. The decrease of mobility with increasing magnetic field intensity B is usually expressed by the following equation, where a constant collision frequency, ν_c, is assumed:

$$\mu_e = \frac{e}{m} \frac{\nu_c}{\nu_c^2 + (eB/m)^2} \tag{1}$$

e and m are the electron charge and mass, respectively. The effect of the magnetic field on the conductivity through its impact on the electron density is usually not considered as being essential. However, as will be shown, the change in electron density due to magnetic field controlled electron generation and depletion processes can affect the conductivity in a similar way as through changes in the mobility.

The concept for a magnetically controlled reduction of electron density and consequent reduction of conductivity in the positive column of a glow discharge is based on the following considerations. The electron energy distribution $f(\varepsilon,E/N,B/N)$ in the positive column is shifted towards smaller electron energies ε, when a transverse magnetic field is applied. This leads to a reduction of the ionization rate coefficient, which is given as:

$$k_i = \frac{2}{m}^{1/2} \int_0^\infty f(\varepsilon,E/N,B/N)\varepsilon^{1/2}\sigma_i(\varepsilon)d\varepsilon \tag{2}$$

σ_i is the ionization cross section and N is the gas density. If electronegative gases with attachment cross section peaking at low energies are used, an increase in attachment rate will occur, due to the shift in the electron energy distribution. The attachment rate coefficient is :

$$k_a = \frac{2}{m}^{1/2} \int_0^\infty f(\varepsilon,E/N,B/N)\varepsilon^{1/2}\sigma_a(\varepsilon)d\varepsilon \tag{3}$$

with σ_a being the attachment cross section. Attachment serves as an additional mechanism to reduce the electron density. The effect of the magnetic field on the carrier density could in this case - that means by using suitable electronegative gases - be more effective in changing the conductivity of the positive column than the change in mobility as given in Equation (1).

COMPUTATIONAL RESULTS

Monte-Carlo calculations were performed to simulate the positive column of glow discharges in gas mixtures of He and SF_6 at 10 Torr when a transverse magnetic field is applied. The gas mixtures, which were chosen for our studies, were 20% SF_6/80% He, and 5% SF_6/85% He at 10 Torr pressure. Sulfur hexafluoride (SF_6) was chosen as the attacher for this work because of its strong attachment peak at a very low energy, and the fact that a total set of collisional cross sections are more readily found than those for other candidate gases with similar attachment cross sections. For the first calculations SF_6-data compiled by Kline (1979) were used. The results of these calculations are published by Cooper, Schoenbach and Schaefer (1986). More recent calculations are based on SF_6 cross sections provided by Phelps (1985). Even though there were differences in the two sets of cross sections, the computed electron energy

distributions in the positive column were almost identical. The cross sections for He, which serves as buffer gas, were taken from a paper by Hayashi (1981).

Steady state characteristics

To describe the steady state characteristics of the positive column, spatial uniformity of electric and magnetic field intensity was assumed. A Monte-Carlo code was used to calculate the electron-energy distribution, ionization rate coefficient, attachment rate coefficient, collision frequency and drift velocity in the mixtures of SF_6 and He. Because of the steady state situation and the homogeneity of the gas and the applied fields, it is sufficient to simulate the motion of one single electron. From ergodicity it can be assumed that a sufficiently long path of this sample electron will give information on the behavior of the entire electron gas. Each run of the program considered 10^6 collisions. The range of the reduced electric field E/N investigated was 60 to 2400 Td and the range of magnetic flux density, B, was from 0 to 9 Tesla.

Results of these calculation are shown in Fig. 1 for 20% SF_6/80% He. The ionization rate coefficient and the attachment rate coefficient are plotted in Fig. 1a and Fig. 1b, respectively. The collision frequency v_c and the drift velocity v_d are shown in Fig. 2a and 2b as a function of reduced field between 50 and 400 Td, with the magnetic field intensity B as parameter. The drift velocity shows the expected decay with increasing magnetic field, however it is due to the reduction in collision freqency with increasing B not as strong as predicted by the simplified model(Equation 1). The main effect of a magnetic field on the conductivity of the electro-negative gas mixture seems to be the reduction of the effective ioniza tion rate coefficient (k_i - k_a), rather than the reduction of the mobility u_e.

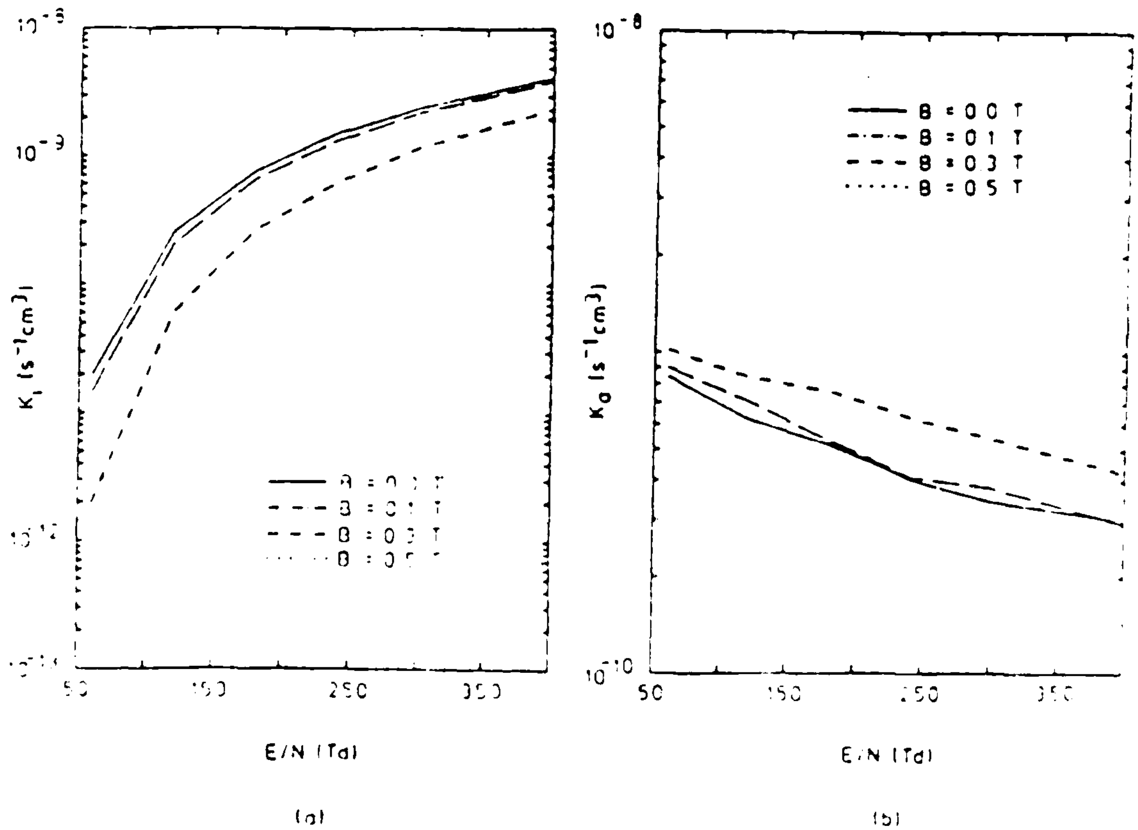

Fig. 1. Ionization (a) and attachment (b) rate coefficient as a function of E/N for various magnetic flux densities, p = 10 torr, 20% SF_6 - 80% He

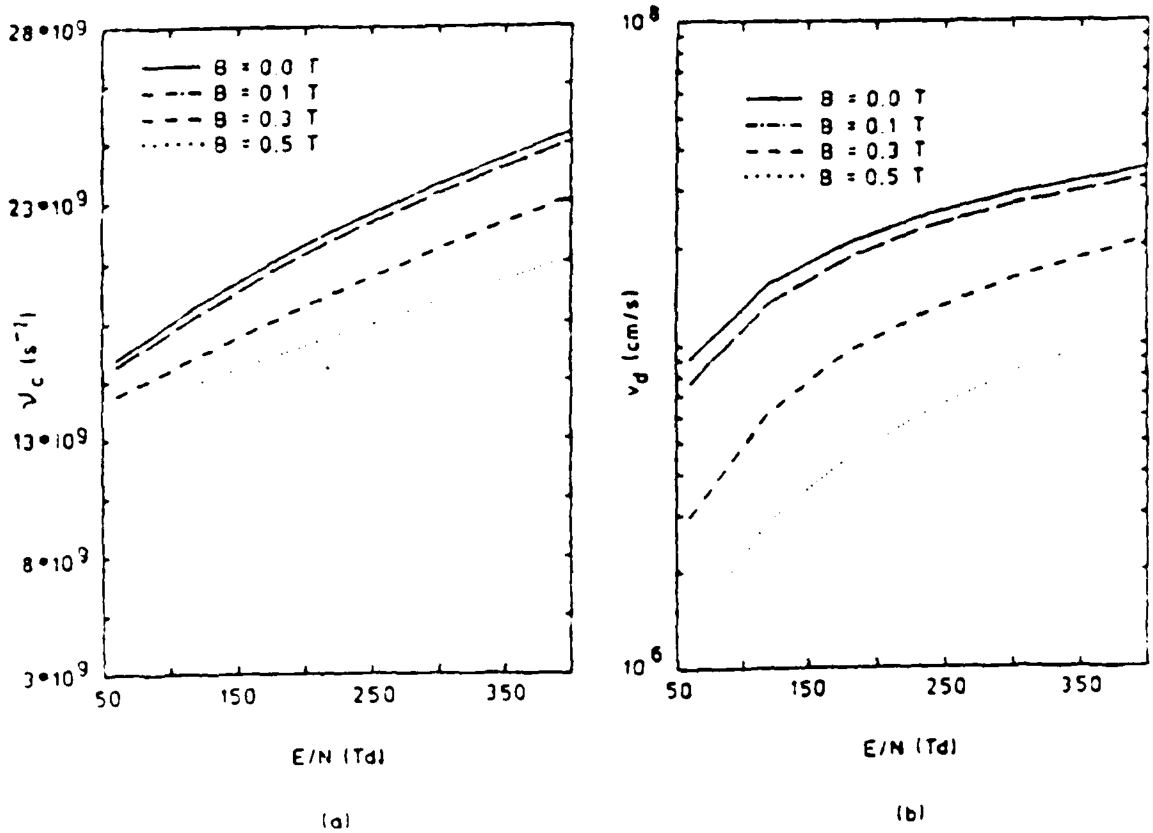

Fig. 2. Collision frequency (a) and drift velocity (b) as a function of E/N for various magnetic flux densities, p = 10 torr, 20% SF_6 - 80% He.

The computed rate coefficients k_i and k_a can be used in a simplified continuity equation for electrons, where detachment, recombination and diffusion processes are neglected, to calculate the equilibrium reduced field strength E/N for the positive column of a discharge plasma as a function of B/N. This equilibrium E/N, or limiting E/N, is the electric field intensity at which

$$\frac{du_e}{dt} = k_i N n_e - k_a N_a n_e = 0 \qquad (4)$$

The results from such calculations are shown in Fig. 3 for 20% SF_6/80% He and 5% SF_6/95% He. Except for small values of B/N, the E/N versus B/N curves increase linearly with a slope of E/B = 1 (kV/cm)/Tesla and 0.25 (kV/cm)/Tesla, respectively. That means that the application of a magnetic field of 1 Tesla forces an increase of the applied voltage across the positive column of a glow discharge in 20% SF_6/80% He by 1 kV*d, where d is the length of the positive column in cm, in order to sustain the discharge. If the electrical circuit of

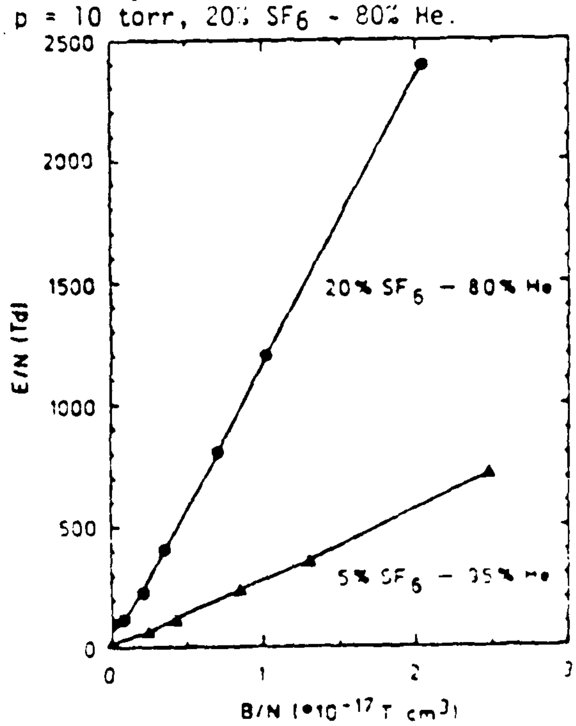

Fig. 3. Calculated reduced equilibrium field intensity E/N in the positive column as a function of reduced magnetic flux density B/N

the glow discharge does not allow an increase in voltage, the discharge will be turned off by the magnetic field.

Transient behavior

To describe the temporal response of the positive column to the application of a transverse magnetic field, a Monte-Carlo code was developed where 10^4 electrons were simulated independently with appropriate distributions of initial conditions. The equilibrium electron energy distribution in the positive column at zero magnetic field was chosen as the initial distribution. This is, for 20% SF_6/80% He, the distribution at E/N = 105 Td. At time t = 0 a step magnetic field was applied and the temporal development of the energy distribution of the initial 10^4 electrons was recorded until the distribution approaches the steady state curve for the applied magnetic field with the electric field being constant. The temporal development of the electron energy distribution is shown in Fig. 4 for E/N = 105 Td and B = 0.5 T * u(t), where u(t) describes the step behavior of the magnetic field.

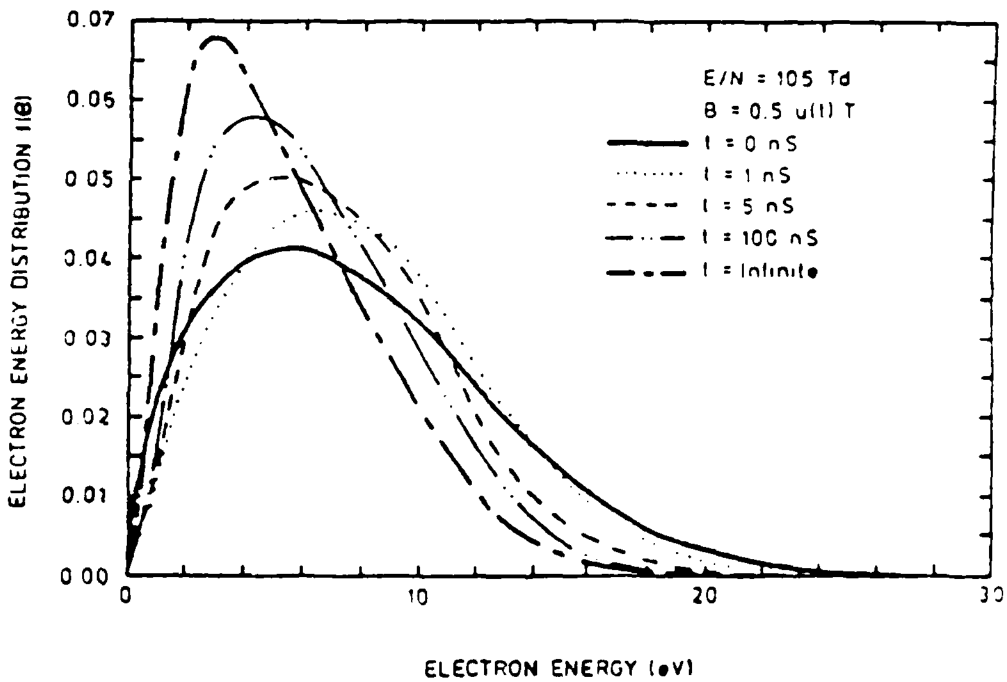

Fig. 4. Temporal change in electron energy distribution after application of a step magnetic field of B = 0.5 T u(t).

The temporal change of the ionization rate coefficient k_i and the attachment rate coefficient k_a are shown in Fig. 5. The rate coefficient for attachment is modified according to the ratio of attaching gas density N_a to total gas density N to allow direct comparison between electron generation and depletion rate in this specific gas mixture. At t = 0 where these processes are in equilibrium, k_i and $k_a*(N_a/N)$ are equal. During the first nanosecond they both decrease by the same amount, then, however the two curves approach different steady state values, the reduced attachment rate coefficient being larger by about a factor of two. The temporal development of the electron density can be estimated by using the continuity equation:

$$\frac{dn_e}{dt} = N(k_i - \frac{N_a}{N} k_a) n_e \qquad (5)$$

For steady state values of k_i and k_a this differential equation can be integrated analytically and the result is

$$n_e = h_e \exp[N(k_i - \frac{N_a}{N} k_a)t]$$

The theoretical result corresponds to an experiment where the voltage is kept at a constant value after the magnetic field is applied. This is the situation which is characteristic for capacitive discharge circuits. Consequently, [illegible] capacitive discharge circ[illegible] a 20% SF_6/ 80% He glow d[illegible]arge used as a switch should [illegible]n off with a time constant of T = 100 ns when a magnetic field of 0.5 Tesla is applied.

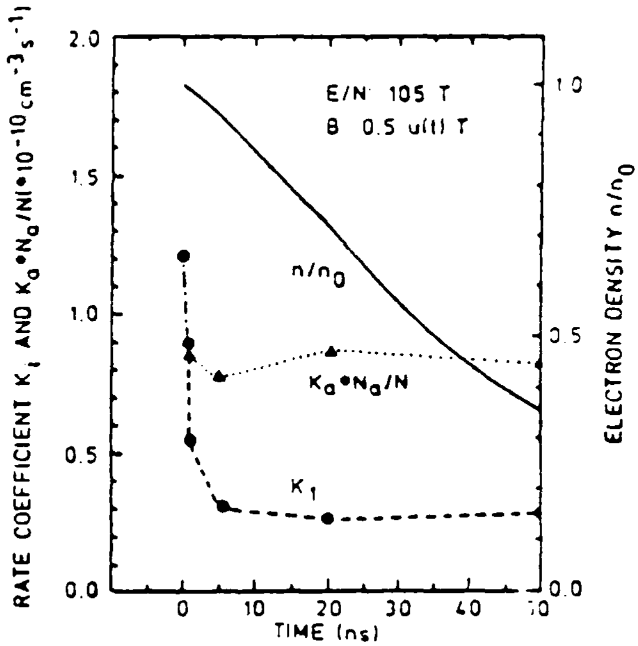

Fig. 5. Computed temporal change of ionization and reduced attachment rate coefficients k_i and k_a x N_a/N, respectively, and corresponding decay in normalized electron density n/n_0 after the application of a step magnetic field to an ionized gas (80% He:20% SF_6) at time T = 0.

EXPERIMENTAL RESULTS

A schematic of the experimental setup is shown in Fig. 6. The glow discharge is produced by overvolting a radial gap, with the center rod being the cathode. The cathode area is about 100 cm^2. The anode consists of a set of rods arranged to form a cylinder around the cathode. The discharge is driven by a 50-Ohm cable. It is designed to deliver voltage pulses of up to 40 kV with ns-risetimes to the discharge chamber. A coil around the coaxial discharge chamber allows application of axial magnetic fields up to 1.2 Tesla. The discharge current is measured with a Rogowski-coil, the voltage across the discharge with a capacitive voltage probe.

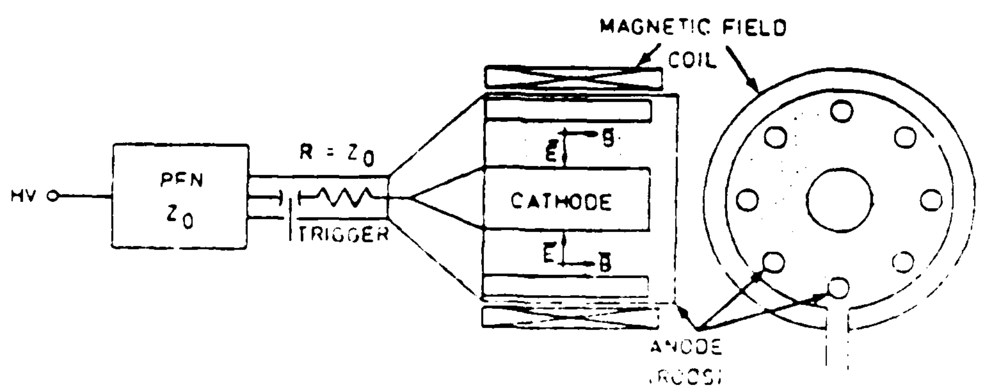

Fig. 6. Experimental setup, side view and end-on view

After a large overvoltage is applied to the discharge chamber, the discharge voltage and current approach a steady state in some tens of nanoseconds characterized by a discharge resistance in the range of several tens of Ohm. With magnetic fields applied, the duration of the steady state phase is less determined by the discharge circuit (200 ns transmission line) but rather by transition into

a low resistance arc. The onset of the glow-to-arc transition varies statistically but generally it sets in earlier with increasing magnetic field and higher current densities.

The measured steady state current-voltage characteristics for 80% He/ 20% SF_6 with the magnetic field strength as parameter is plotted in Fig. 7a. The data points represent experimental values with an error of about 10%, due to the uncertainty in voltage data. According to our simple model for the positive column (Equation 4), E/N and therefore the voltage -- at least in the positive column -- should not depend on the current. At higher magnetic field strengths, however, there is a distinct increase of voltage with increasing current. This current density dependent effect might be due to the increasing importance of recombination processes, which have been neglected in our calculations.

The voltage is rising with increasing magnetic field as expected from our theoretical studies. Besides this qualitative correspondence there is a reasonable agreement between theory and experiment with respect to the rate of change of electric field with increasing magnetic field. In Fig. 7b the theoretical E/N versus B/N curve is compared with curves derived from experimentally obtained values at current densities of 0.6 A/cm^2 and 1 A/cm^2. For these curves it was assumed that the positive column extends over the entire distance between the electrodes and that E/N is constant in this region. The agreement in the slopes of experimentally and theoretically obtained E/N versus B/N curves becomes better with increasing current density.

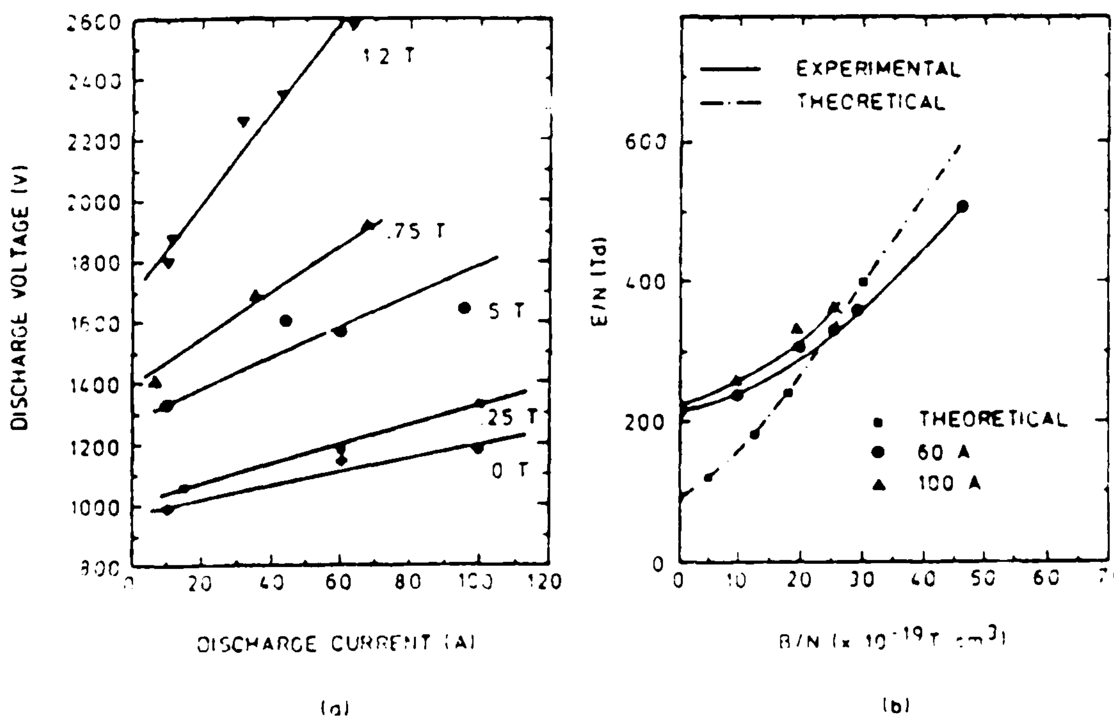

Fig. 7(a). Voltage current characteristics for a glow discharge in 20% SF_6 - 80% He at 8 torr with magnetic field intensity as a parameter.

Fig. 7(b). E/N values as a function of magnetic field intensity for current densities of 0.6 A/cm^2, 1.0 A/cm^2 (60 A and 100 A) and the computed curve which is independent of current density.

CONCLUSION

Theoretical investigations of the positive column in a magnetically controlled glow discharge in SF_6/He have been performed, both steady state and time dependent. The steady state calculations indicate that a magnetically induced increase in electric field strength, corresponding to an increase in resistance, of about 1 kV/Tesla can be expected in a 20% SF_6/80% He mixture. This result is in agreement with our experimental observations (Fig. 7). The measured rate of change in voltage with magnetic field intensity above 0.3 Tesla approaches the value 2 kV/Tesla at a gap distance of 2 cm. At current densities in excess of 1 A/cm^2, corresponding to currents greater than 100 A in our system, it is expected that the voltage across the discharge is determined more and more by the cathode fall rather than by the positive column. Therefore, and because of the importance of this region for the stability of the discharge it is planned to expand the theoretical and experimental investigation to the cathode fall. The time-dependent investigations of the positive column give an estimate of the time scale of the dynamic response of the plasma to changes in the magnetic field for a constant electric field. A typical time constant for the decay of electron density in the positive column is 100 ns for applied magnetic fields of 0.5 Tesla.

Both experimental and theoretical results indicate that it is possible to use magnetically controlled glow discharges as opening switches for inductive energy storage systems or as a means to shorten the recovery time in low pressure closing switches operated at high repetition rates. A problem which imposes restraints to their use as switches is the relatively high forward voltage at zero magnetic field, which in our system is greater than one kV and is increasing with current density. A considerable contribution to this voltage comes from the cathode fall. A way to reduce the cathode fall voltage without sacrificing current density is to use a hollow cathode (Schaefer and co-workers, 1984). First experiments with a hollow cathode showed that the discharge voltage with no magnetic field applied is reduced by a factor of two. We assume that further reduction of the forward voltage drop is possible by optimizing cathode material and geometry, and gas composition.

ACKNOWLEDGEMENT

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APPENDIX D

Analysis of the Cathode Fall of Glow Discharges in a He/SF_6 Gas Mixture

5th Symposium on Gaseous Dialectrics, Knoxville, TN, May 1987

ANALYSIS OF THE CATHODE FALL OF GLOW DISCHARGES IN A He/SF_6 GAS MIXTURE

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ABSTRACT

A Monte-Carlo code was used to calculate the electron energy distributions and the transport and rate coefficients in the cathode fall region of glow discharges in a He/SF_6 gas mixture. The charge carrier densities and the current densities were computed by means of a continuum model. Through an iterative procedure a self consistent solution for the cathode fall was approached. In order to study the influence of externally applied magnetic fields on the cathode fall, the calculations were repeated for a transverse magnetic field of 0.5 Tesla.

KEYWORDS

Discharge modeling, cathode fall, SF_6, magnetic field

INTRODUCTION

Glow discharges are spatially characterized by four regions: the cathode fall, the negative glow, the positive column, and the anode fall. The power consumption in the discharge is to a large extent determined by the processes in the cathode fall region. For current-densities 1 A/cm^2 the voltage V_c in the "abnormal" cathode fall reaches values in the order of kV over the distance of less than one mm (von Engel ,1983).

There are numerous efforts to model glow discharges (Davies, 1986). Since the positive column can be considered as a homogenous plasma, the calculation of transport and rate coefficients in this part of the discharge requires only the use of zero-order Monte-Carlo codes (Cooper, Schoenbach, and Schaefer, 1986). In the cathode fall region, the electric field near the cathode is very high and varies rapidly in space. It is therefore not permissible to use cathode fall models which assume equilibrium of the charged particles with the electric field. The fall characteristic should be studied by microscopic methods such as Monte-Carlo techniques or the Boltzmann equation.

Monte-Carlo simulations of the cathode fall have been performed by Tran and co-workers (1977), Davies and co-workers (1980), Boeuf and Marode (1982), Segur and co-workers (1983), and Razdan, Capjack, and Seguin (1985). All of these studies, however, were performed for "normal" cathode falls in He, assuming

a voltage of about 400 V over a distance of 1 cm. We have developed a self consistent, steady state model of the abnormal cathode fall in a gas discharge which is operated in a gas mixture containing SF_6. Because of the potential importance of glow discharges in electronegative gases for switches (Cooper, Schoenbach, and Schaefer, 1986) and for semiconductor processing, we have also studied the effect of a transverse magnetic field as a means to control the density and energy distribution of charged particles in the cathode fall region.

METHOD

In figure 1 the modeling procedure is shown in form of a flow-diagram. The initial electric field was assumed to be linearly decreasing over a distance of 0.5 mm (cathode fall) and then to stay constant (positive column). Its maximum value, at the cathode surface, was set to 18000 Td, according to a cathode fall voltage of 1.5 kV. The minimum value, the electric field in the positive column, was calculated by means of a zero order Monte-Carlo code. For a 80% He/ 20% SF_6 gas mixture at a total pressure of 10 Torr it was found to be 105 Td (Schoenbach and co-workers, 1987). These calculations and the ones described in the following were based on SF_6 cross-sections for vibrational and electronic excitation, ionization, attachment, and momentum transfer provided by Phelps (1985). The rate coefficients for ion-ion recombination and for collisional detachment were assumed to be 2×10^{-7} $cm^3 s^{-1}$ and 10^{-6} $cm^3 s^{-1}$ respectively. The rate coefficient for electron-ion recombination was taken from a paper by Biondi (1982). The ion-mobilities were obtained from compilation by Ellis et al.(1976). The cross-sections for He, which serves as buffer gas, were taken from a paper by Hayashi (1981).

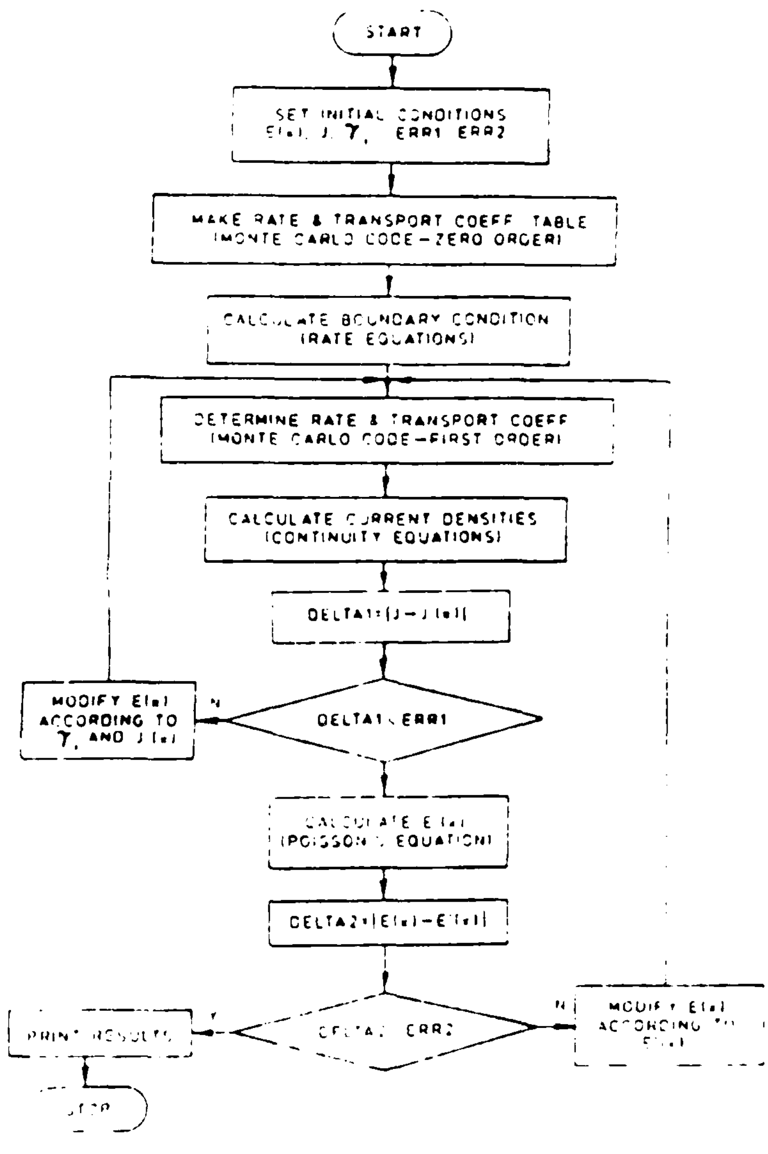

Fig. 1. Flow diagram for the discharge modeling.

A one dimensional Monte-Carlo code was used to obtain the electron energy distributions as a function of position along the discharge axis.
Ensembles of 500 to 10000 electrons were seeded at the cathode to simulate the cathode fall. The initial distribution of the electrons, when leaving the cathode, was assumed to be constant between 0 and 10 eV and zero for higher energies (Hagstrum, 1956). Knowing the electron distribution functions allowed to calculate the rate coefficients, such as ionization and attachment rate coefficient, and the electron drift velocity as a function of position. These data were used to determine the spatial distribution of electrons, positive and negative ions, and the current densities for the different species by means of a set of continuity equations. Processes considered in the continuity equations are ionization, electron-ion and ion-ion recombination, attachment and collisional detachment. Integration of these equations was performed by using the previously calculated values for the particle density and the current density in the positive column as boundary values. The initial electric field distribution was then modified to match the condition for total current density along the discharge axis:

$$dJ/dx = 0 \qquad (1)$$

The boundary condition at the cathode is determined by secondary ionization processes that can occur at this electrode. Neglecting any photon processes, the boundary condition at the cathode is given by:

$$J_e(x=0) = \gamma_i \, J_+(x=0) \qquad (2)$$

here J_e and J_+ are the current densities for electrons and positive ions, respectively, and γ_i is defined to be the probability of electron emission per incident ion. In order to satisfy this condition for a certain γ_i the cathode fall distance was adjusted leaving the electric field distribution unaltered in the newly defined cathode fall region.

The procedure described in the paragraph above is then repeated to obtain a new set of solutions for particle and current density, which match the boundary conditions better. By means of Poisson's equation the electric field distribution is subsequently modified and the simulation is performed again. By carefully choosing the initial field distribution it seems to be possible to obtain a reasonably accurate, self consistent, result for the electric field and the particle and current distributions after the first set of iterations.

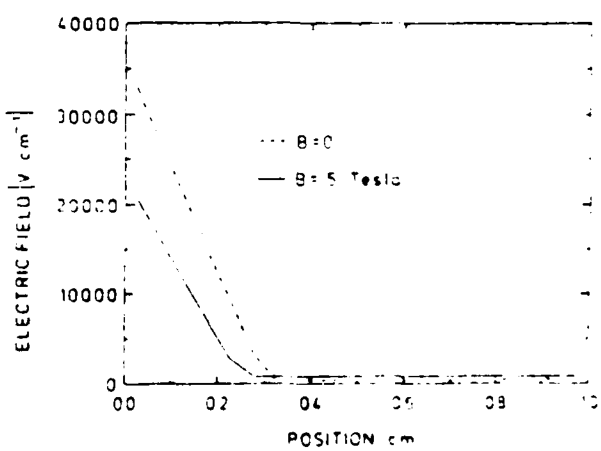

Fig. 2. Electric field distribution in the cathode fall and positive column.

RESULTS

Figure 2 shows the calculated electric field distributions for zero magnetic field and applied transverse magnetic field of 0.5 Tesla. The electric field for

B=0 is, after the first set of iterations still linear except the part adjacent to the positive column (negative glow), however, the cathode fall distance is shorter than the assumed fall length by about a factor of two. Also, the electric field intensity at the cathode surface is reduced by a factor of 1.5. The charge carrier distribution is plotted in Fig. 3. As expected, the electron density in the cathode fall region decays rapidly in the direction towards the cathode. The negative ion distribution is similar, due to low attachment rate in the high field region in the vicinity of the cathode. The distribution of the positive ions does not vary that drastically, however, it is certainly not constant over the cathode fall distance, as assumed in early cathode fall models (Ward, 1958).

The carrier distribution in the negative glow is very sensitive to variations in the electric field in this region. The electrons leaving the cathode fall carry a high momentum which causes a high ionization rate in the negative glow. In order to satisfy the current density condition (1) small electric field intensities or even reversed fields must be assumed to obtain a self-consistent

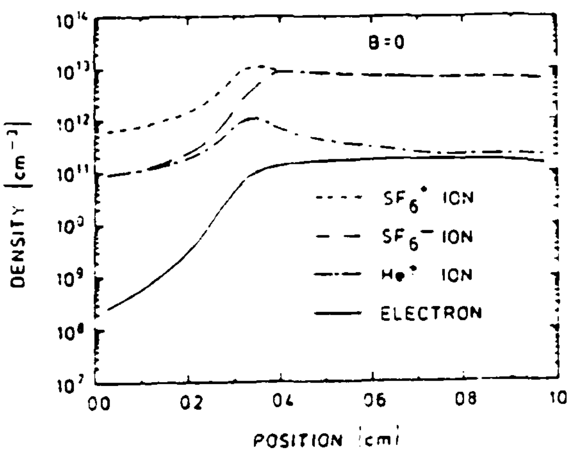

Fig. 3. Charge carrier densities in the cathode fall and positive column.

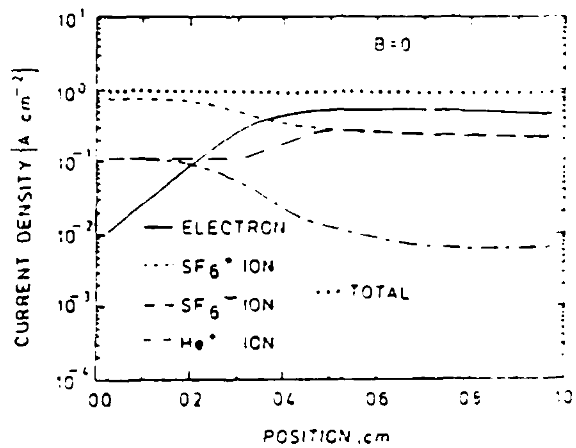

Fig. 4. Current densities in the cathode fall and positive column.

solution. On the other hand the attachment rate can reach very large values if the electric field is lowered too much. This makes it very difficult to adjust the electric field in this region.

Current densities for electrons, negative and positive ions, are shown in Fig. 4. Most remarkable is that according to our calculations a large portion of the current (50%) even in the positive column is carried by SF_6^- ions rather than electrons. The electron current reduces to value of .01 of the positive ion current at the cathode surface satisfying the condition in equation 2.

For these calculations it was assumed that influence of the magnetic field generated by the discharge current can be neglected and that no external magnetic field is applied. It is known that magnetic fields can drastically change the discharge characteristics through their impact on the electron energy distribution function (Allis and Allen, 1937). It was found that in a gas mixture containing SF_6, the application of magnetic fields transverse to the electric field causes an increase in the limiting or equilibrium electric field intensity in the positive column of a gas discharge (Raju and Dincer, 1985; Cooper, Schoenbach and Schaefer, 1986). In order to explore its influence on the cathode fall the simulation described above was performed for a crossed field

configuration, with a transverse magnetic field of 0.5 Tesla applied.

Fig. 2 shows the electric field in the cathode fall region. The magnetic field obviously causes a reduction of the electric field intensity in the cathode fall contrary to its effect in the positive column (Cooper, Schoenbach and Schaefer, 1986). The cathode fall voltage is reduced to about 250 V, down from 300 V for the cathode fall in the magnetic field free case.
In Fig. 5 the electron drift velocities for the case with and without magnetic field are compared. The electron drift velocity is lowered in crossed fields over the entire discharge length, except close to the cathode, by about a factor of 4. Fig. 6 shows the ionization and attachment rate coefficients for B=0 and B=0.5 Tesla. The application of a transverse magnetic field obviously leads to a reduction of the ionization rate and an increase in attachment. These changes are caused by the shift of electron energy distribution towards smaller

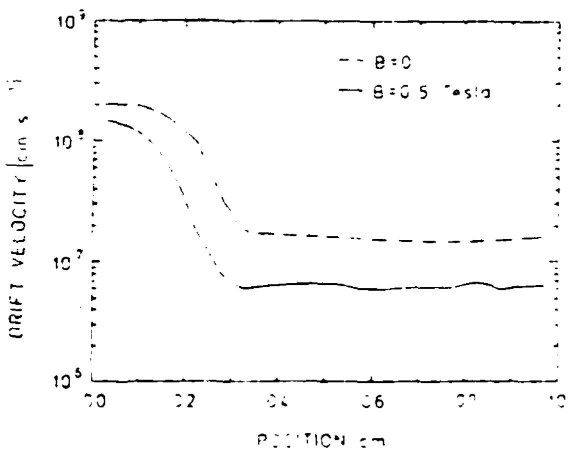

Fig. 5. Electron drift velocity in the cathode fall and positive column.

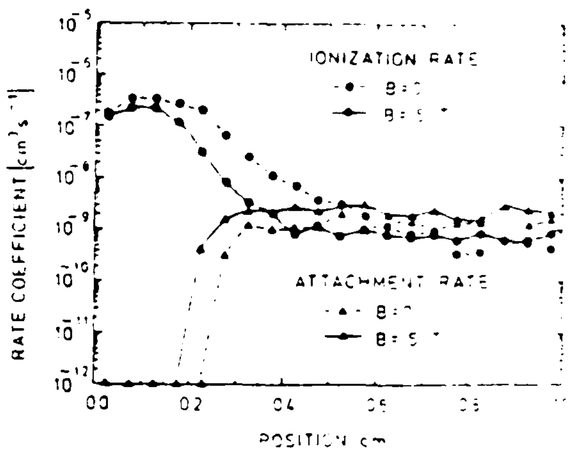

Fig. 6. Ionization and attachment rate coefficients in the cathode fall and positive column.

energies when a magnetic field is applied perpendicular to the electric field of the discharge (Cooper, Schoenbach and Schaefer, 1986).

CONCLUSION

A simulation technique for the cathode fall of glow discharges has been developed which allows us to obtain a self consistent solution for the cathode fall. Knowing the gas properties (cross sections, rate coefficients) and the electron emission processes at the cathode (γ-coefficients) the current-voltage characteristic for the cathode fall can be derived. The method can easily be extended to simulate the entire discharge.

The simulation technique was applied to a gas discharge in a gas mixture containing SF_6. The cathode fall distance at current densities of 1 A/cm² is much smaller than it was assumed for normal cathode falls in He (Tran and co-workers, 1977). The electric field intensity for these abnormal glow discharges reaches values of more than 30000 Td at the cathode surface, far above the values which are assumed for normal glow discharges in noble gases. The application of

transverse magnetic fields causes a reduction of the electric field intensity in the cathode region and an increase in the density of negative ions at this electrode. This result indicates that magnetic fields could be used to control the density and energy of negative ions in plasma devices for semiconductor surface processing.

ACKNOWLEDGEMENT

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APPENDIX E

Abstract of Presentation at 1987 IEEE International Conference on Plasma Science Washington, D.C. June 1987

Abstract Submitted for the

1987 IEEE International Conference on Plasma Science

June 1-3, 1987

THE EFFECT OF TRANSVERSE MAGNETIC FIELDS ON GLOW DISCHARGES IN ELECTRONEGATIVE GASES

K. H. Schoenbach, T. J. Powers, S. T. Ko, and V. K. Lakdawala, Old Dominion University, Norfolk, Va.

The effect of a transverse magnetic field on the steady state characteristics of glow discharges in He/SF_6 gas mixtures was studied experimentally and theoretically. A coaxial discharge system was used which allows application of axial magnetic fields up to 1.2 Tesla. Measurements of the discharge voltage and current in a He/SF_6 mixture at a pressure of 8 Torr were performed at varying magnetic fields. At current densities of 1 A/cm^2 the discharge voltage was found to increase with increasing magnetic field at a rate of 2 kV/Tesla for a gap distance of 2 cm.

A one-dimensional, self consistent discharge model was developed. Monte-Carlo codes were used to calculate the electron energy distributions and the transport and rate coefficients in the positive column and in the cathode fall. The charge carrier densities and the current densities for electrons and ions along the discharge axis were subsequently computed by means of a continuum model. A self consistent solution for the cathode fall was obtained through an iterative procedure. The calculations were performed for discharges in 80% He/ 20% SF_6 mixture with no external magnetic field and transverse magnetic field of B = 0.5 Tesla, respectively.

The calculation of the electric field in the positive column gave values of 100 Td for B = 0 and increased to 300 Td when a magnetic field of .5 Tesla was applied. In the cathode fall region the application of a magnetic field had the opposite effect on the electric field intensity. At the cathode surface values of 35000 Td were obtained in the magnetic field free case compared to 20000 Td for the discharge with B = 0.5 Tesla. The cathode fall distance was with 0.3 mm about the same under both conditions. The electric field results of the discharge simulation agreed well with the field values obtained from measurements of the discharge voltage.

*Supported by the Office of Naval Research under contract No. N00014-85-K-0602.

Subject Category and Number

ARC TECHNOLOGY

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Special requests for equipment

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APPENDIX F

Abstract of Presentation at 1987 Gaseous
Electronics Conference, Atlanta, GA, October 1987.

Analysis of the Cathode Fall of Abnormal Glow Discharges in an Electronegative Gas*, K. H. Schoenbach and Hao Chen, Old Dominion University, Norfolk, VA, - The cathode fall and the positive column of a glow discharge in a SF_6/He gas mixture was modeled for current densities in the range of 1 A/cm^2. A one dimensional Monte-Carlo code was used to calculate the electron energy distributions and the transport and rate coefficients as a function of position in the discharge, assuming a linearly varying electric field in the cathode fall region. Subsequently the charge carrier densities and electron and ion current densities were computed by means of a continuum model. The results were used to correct the assumed electric field distribution and through an iterative procedure to approach a self consistent solution for the cathode fall. The influence of a transverse magnetic field on the glow discharge was studied with the same technique. The calculated discharge voltages were compared with experimentally obtained values.

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